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BIOLOGICAL EFFECTIVENESS OF IONIZING DIATION WITHIN SHELTERS.(U)
SEP 53 V P BOND , R E CARTER , J S R D

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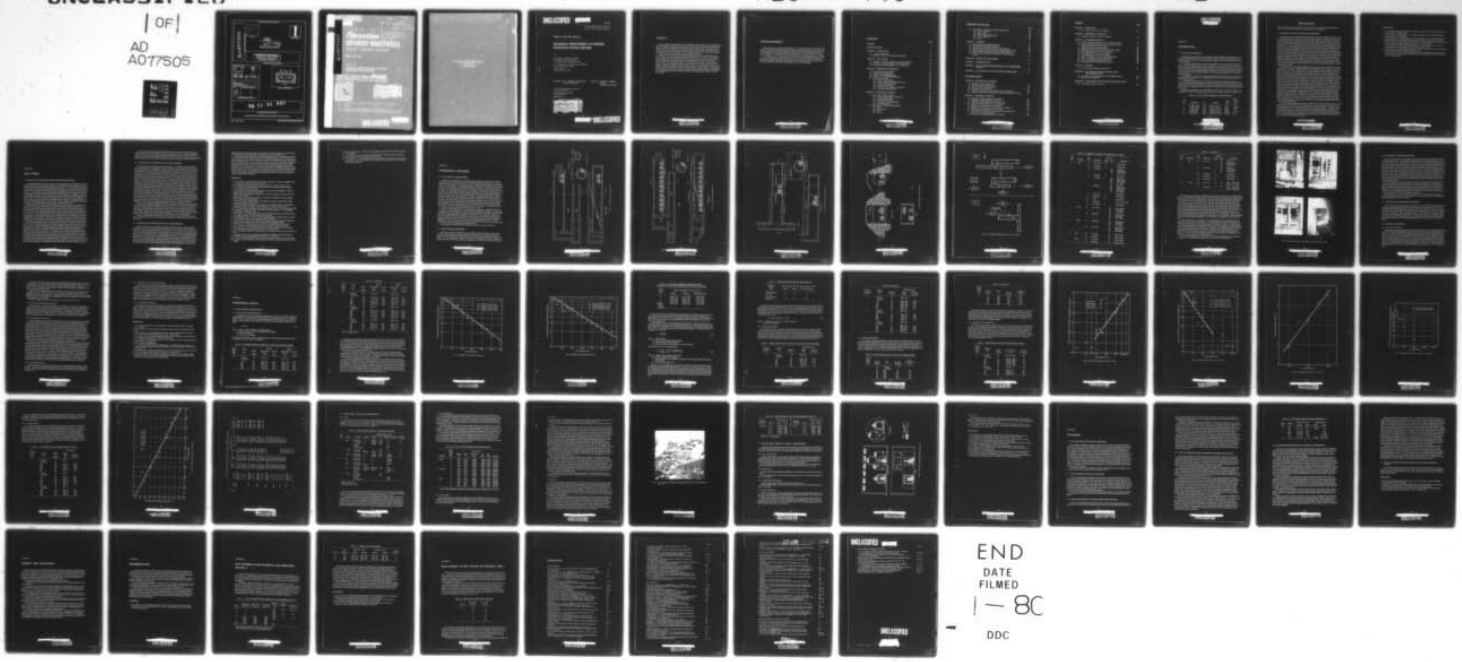

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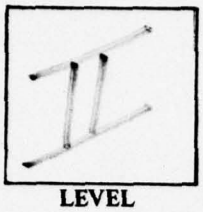

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Operation UPSHOT-KNOTHOLE

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March - June 1953

Project 23.1

BIOLOGICAL EFFECTIVENESS OF IONIZING RADIATION WITHIN SHELTERS

U.S. NAVAL RADIOLOGICAL DEFENSE LABORATORY
AND
NAVAL MEDICAL RESEARCH INSTITUTE

WT-793

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Report to the Test Director

BIOLOGICAL EFFECTIVENESS OF IONIZING RADIATION WITHIN SHELTERS

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ABSTRACT

Direct biological measurements of the total radiation hazard within earth-protected Atomic Energy Commission communal shelters were carried out in five shots of the Upshot-Knothole series. Animals were exposed in thin aluminum and in lead-protected containers in order to estimate the neutron contribution to the total biologically effective dose. Mice and dogs were used. Biological end points employed included mortality, hematology, spleen-thymus weights, gut weights, and uptake of radioactive iron in hematopoietic tissue.

Satisfactory correlations between physical measurements of dose and biological effect were obtained. The neutron hazard within shelters having 3 ft 8 in. or more of earth overlay was not appreciable with outside sulfur fluxes of 2.4×10^{11} n/cm^2 or less (a 20-kt weapon at 700 yd), regardless of the incident angle of the bomb radiation. Accurate predictions for greater fluxes or less thickness of earth are not possible from the data. The contribution of neutrons to the total biologically effective dose was found not to increase over the free-air situation following transmission through the earth overlay, and hence gamma is the controlling radiation hazard within shelters exposed to large-diameter implosion weapons. Although significant gamma dose levels were found in certain prototype shelter structures, no statement of the probable degree of hazard is warranted because of probable gamma "leaks" in the structures studied.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to R. L. Corsbie, Director, Civil Effects Test Group, for his continuous attention and kindly advice, without which the project could not have been accomplished. The active support and contributions of the following individuals are also acknowledged: Dr. John Bugher, CAPT W. E. Kellum, CAPT T. Wilmon, CAPT J. L. Bird, Dr. E. P. Cooper, Dr. M. C. Fishler, Miss Pauline Silvia, R. W. Newman, and R. P. Nicolson.

The willing and close cooperation of E. Tochilin and other Upshot-Knothole Project 23.17 personnel in assuring that physical dosimeters were placed to allow maximum utilization in interpreting biological responses is appreciated. The contributions of Dr. E. A. Jerome and Mrs. D. M. Lathrop in analyzing the gut weight data are also acknowledged.

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CHAPTER 1

INTRODUCTION

1.1 PURPOSE OF EXPERIMENT

Upshot-Knothole Project 23.1 was organized to conduct biological measurements inside certain United States Atomic Energy Commission (USAEC) communal-shelter prototypes. Direct biological measurement of potential radiation hazards was considered necessary for the following reasons:

1. Currently available physical neutron-detecting devices were considered inadequate for neutron-spectrum and total-neutron-flux measurements. Biological effects of neutrons were known to be critically dependent on neutron energy as well as total neutron flux; hence the prediction of biological effect using such physical data as were available or could be obtained was not possible. Ionization chambers designed to measure dose in rep delivered by fast neutrons in the presence of a gamma-radiation field were not sufficiently developed to allow prediction of biological effect.

2. Knowledge of the effect of scattering media of appreciable thickness on neutron spectrum did not permit the development of an adequate theoretical model of the shielded situation represented by the shelter.

3. Although certain information is available on weapon neutron effects in the mouse, not enough was known about the penetration of neutrons in tissue to permit the extrapolation of this information to large animals. Therefore the use of large animals was considered necessary in order to attempt evaluation of the neutron hazard in a tissue mass more closely approximating that of man.

Biological measurements of dose within shelters were made on a total of five shots. The detonations used, with kilotonnage, dates of firing, and code names, are listed in Table 1.1. In

Table 1.1 — LIST OF SHOTS, PROJECT 23.1 PARTICIPATION

Shot No.	Date fired	Kt	Location	Code name	Air or tower burst
1	17 March 1953	17.8	Area 3, Yucca	Annie	Tower
3	31 March 1953	0.18	Area 7.5a, Yucca	Ruth	Tower
4	6 April 1953	10.8	Area 7.3, Yucca	Dixie	Air
8	19 May 1953	32.4	Area 3a, Yucca	Harry	Tower
11	4 June 1953	60.0	Area 7.3a, Yucca	Climax	Air

addition to those listed, shot 9 (Encore) was utilized. The small amount of data obtained on mice exposed in lead hemispheres in this shot is included as Appendix A.

1.2 SUMMARY OF PREVIOUS COMPARABLE EXPERIMENTS

No previous direct measurements of biological effects of ionizing radiation have been made in a shielded situation similar to the communal shelters. However, extensive experiments on the biological effects of both gamma and neutron radiation from nuclear weapons in essentially free-air situations have been conducted. Studies of the biological effects of gamma rays were carried out at Operation Greenhouse and are reported in detail in the publications dealing with that operation.[1-4] Both large (dogs and swine) and small (mice) animals were exposed at distances where the gamma-radiation dose, as measured with National Bureau of Standards (NBS) film packs, ranged from approximately 3450 to 190 r. Animals were confined in containers which caused minimal attenuation of the gamma radiation, and in general the dose received by the animals was more than 90 per cent of the free-air dose. For large animals it appeared that the gamma-radiation effects resembled those of conventional X radiation from any supervoltage machine, whereas for the small animals the responses observed could be approximated with X radiation of 200-kvp energy or higher. For the small animals the rbe of the weapon gamma radiation (comparison of rem with rep assuming the readings of the NBS film packs to represent the true measurement of the gamma radiation in roentgens) was essentially unity. Biological test systems employed included mortality observations as well as hematological and organ-weight-change studies.

Experiments on the biological effectiveness of the free-air neutron radiation from nuclear weapons were conducted at Operation Greenhouse and Operation Tumbler-Snapper.[5,6] Animals were exposed to the neutron radiation behind 7-in.-thick lead shields to reduce the gamma radiation to acceptable levels. Originally it was assumed that these shields transmitted the incident neutrons largely unchanged and that the biological effects of the neutron radiation seen within the shields was about 90 per cent of that which would have been observed in free air had the shield not been placed around the specimens. Later evaluations have indicated that actually the shields were only 50 per cent efficient in transmitting the biological effectiveness of the incident neutron flux. This subject is discussed in the report of Project 4.8, Operation Upshot-Knothole.[7] Biological test systems employed in the neutron studies were the same as those employed in the gamma-ray studies with the addition of the measurement of the incorporation of radioactive iron into the red cells of the mouse erythropoietic tissues. Initial results have indicated that the neutron radiation from nuclear weapons is more efficient in producing biological change than was assumed for many years[5,6] and that, from certain weapon types, neutron radiation can exert appreciable biological effects over the lethal and immediate supralethal range of the gamma radiation. Furthermore, neutron measurements have indicated that the biological effects observed are dependent on the spectrum of the neutron radiation. Existing physical dosimeters were unable to account for the variations in effectiveness seen between certain weapon types, a fact which could be explained on the basis that an appreciable portion of the biological changes seen were due to neutrons of energies not recorded by either the gold or sulfur threshold detectors.

Several biological experiments have been conducted with various laboratory neutron sources during the past 15 years. This work is summarized in a previous report.[5] Although the data were interpreted as showing that biological responses to neutron radiation of various energies are qualitatively similar, no useful information on the probable variations in quantitative responses with different or unusual neutron spectra could be gained from the findings reported. Since accurate quantification of response is critical in hazard evaluation, and since neither past field nor laboratory experiments permitted adequate quantitative predictions of anticipated effects, direct biological assay was indicated.

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CHAPTER 2

BASIC THEORY

2.1 GAMMA-RAY AND NEUTRON SPECTRA FROM NUCLEAR WEAPONS

Considerable attention has been devoted to the determination of total gamma-ray flux from nuclear weapons and to the probable spectrum of such radiation at various distances from the bomb. The data indicate that at distances greater than about 3 to 5 mean free paths the gamma radiation falls off exponentially with increasing distance and, when the influence of the inverse-square law is eliminated in the data analysis, has an apparent mean free path of about 360 yd at sea level. This mean-free-path figure indicates an apparent effective energy of about 3 Mev. The apparent high effective energy results from the most energetic or penetrating component of the radiation only, which is a very small fraction of the total number of photons present at any one point. The great majority of the photons present are those which have undergone numerous collisions in air and have been degraded to lower energies. Considerations from measurements of the average energy of the spectrum at various points have indicated that the average energy of the photons present may be of the order of 400 to 800 kv.[1–9]

Measurements of the neutron flux and spectrum from nuclear weapons have been less rewarding. The two detectors that have been used to the greatest extent are gold and sulfur. It has been shown that the sulfur threshold detector measures neutrons with energies greater than about 2.5 to 3 Mev and that the gold detector, when properly shielded with cadmium, can be used to record the neutron population with energies less than the cadmium cutoff (about 0.4 ev). Clearly the use of these two detectors gives little information on the majority of the neutron spectrum. Various estimates of the neutron population in the intermediate energy range (energies between the cadmium cutoff and about 3 Mev) have been made, and although these indicate that the total population in this portion of the spectrum should equal that in the gold detecting range,[10] this conclusion has not been confirmed experimentally in previous operations.

Since a considerable portion of the biological effect of neutron radiation could result from neutrons in this intermediate range,[11] the careful evaluation of the contribution of these neutrons is critical. Certain experiments at Operation Upshot-Knothole were designed to attempt to enumerate the neutrons in the intermediate energy range using threshold detectors with thresholds in the range 0.1 to 3.0 Mev. The details of these preliminary investigations are given in the reports of those projects.[12–14] In general, these reports indicated that the total intermediate neutron population was more nearly five times the gold-measured neutron population. Furthermore, these measurements suggested that the distribution of neutrons within the intermediate energy range and the relation between intermediate and fast or slow neutrons could vary considerably in different shielded situations. Although these measurements are still too scanty to be correlated with biological measurements made, they represent one of the most encouraging developments in the problem of determining biological effect of weapon neutrons.

In general, past data with gold and sulfur detectors have indicated that the slow-neutron flux is about 15 times the fast-neutron flux. It has been assumed that, for conventional fission weapons, the spectrum from different weapons is essentially the same. Marked variations in the total number of neutrons escaping the weapon assembly per kiloton yield have been observed. Additional discussions of the neutron radiation from nuclear weapons are given elsewhere.[11,15,16]

2.2 ATTENUATION OF GAMMA RADIATION IN THICK ABSORBERS

The problem of the attenuation of gamma radiation to be expected in shielded situations was of great importance in attempting to predict biological hazards within the Atomic Energy Commission (AEC) communal shelters. Although previous experimental and theoretical work dealing with the general problem of attenuation of gamma radiation in thick absorbers is far too extensive to summarize adequately in this report, several recent reports are pertinent to the problem as encountered in the field. Theoretical evaluations of the spectral changes in X and gamma radiation to be expected have been developed,[17] and experimental confirmation of portions of the development has been obtained.[18–20] In general, these reports indicate that the degree of penetration of gamma radiation depends on the highest energy component of the incident beam. The thick shielding material over a communal shelter acts as an effective filter, and incident radiations soon reach equilibrium after entering the scattering medium. That is, the number of secondary gamma photons (and electrons) produced equal the number which are totally lost through annihilation reactions, and the spectrum of the radiation remains constant with further penetration. Under these circumstances the incident radiation may be considered as a hard primary beam which gives rise, in any unit volume through which it passes, to a large number of secondary scattered photons and electrons. The total dose delivered in any unit volume results from these secondary radiations, the hard primary component being only a very small fraction of the total number of ionizing rays present. Yet the degree of penetration of the radiation will be governed entirely by the absorption characteristics of the hard or penetrating component of the incident beam, and the fall-off in total dose with increasing depth of penetration in the scatterer will follow the penetration pattern of this hard component.

Thus it would appear that the gamma-radiation level within a shelter could be predicted if the outside or free-air gamma-radiation level were known and if the absorption characteristics of the penetrating component is determined. Furthermore, since it is assumed that the hard component of weapon gamma radiation must be almost completely collimated, especially at short distances from the point of detonation, the total slant range of shielding material transversed along a straight line from the point of detonation to the center of the shelter may be the thickness which determines to a large degree the attenuation of the incident radiation.

It must be emphasized, however, that the entire question of gamma penetration in thick shields is extremely complex, and experimental confirmation of many aspects of current theory is required.

2.3 ATTENUTATION OF NEUTRON RADIATION IN THICK ABSORBERS

Virtually no data on the attenuation of neutrons in Nevada soil exist. Isolated measurements have been made in soil by means of pipes buried in the ground,[21] but in most instances, as was the case with measurements made in open foxholes,[21,22] an indeterminate number of neutrons reached the detectors through the top opening of the containing cavity. As a general rule of thumb, it was assumed that fast or sulfur-measured neutrons would be attenuated by approximately a factor of 10 for each 2 ft of earth penetrated. Furthermore, it was assumed that the Nevada desert soil would contain sufficient boron to capture nearly all incident epithermal or thermal neutrons. Experimental confirmation of this latter assumption was lacking. It was considered that fast and intermediate-energy neutrons, not directly captured in one of their first encounters with nuclei in the shielding material, would be greatly degraded in energy as they

passed further into the shield, owing to the relatively low atomic weight of the majority of the soil constituents and the large amount of energy lost in each scattering event.

Insufficient knowledge existed to predict whether attenuation of neutron radiation would depend on the shortest slant range through which the radiation passed on the direct line from the point of detonation to the center of the shelter cavity or upon the thickness of the thinnest portion of shielding material over any portion of the shelter. For the slow neutrons it was assumed that their direction in air would be essentially random and that they would therefore diffuse downward from the ground surface to the shelter cavity, making the thinnest portion of the earth shield the critical distance for slow-neutron penetration. The higher the neutron energy, however, the more likely is the beam to be collimated, and it was considered that the same situation discussed in Sec. 2.2 would apply for neutrons with energies of a million electron volts or more. Intermediate-energy neutrons would probably represent a situation somewhere between the slow and fast components.

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CHAPTER 3

EXPERIMENTAL PROCEDURE

3.1 AEC COMMUNAL-SHELTER DESIGN

All animals were exposed in various AEC communal-shelter prototypes. Each shelter consisted of a long tubular section with an access ramp and entryway at one end. The other end of the tubular portion of the shelter was closed. Details of the construction are presented in the report of Project 24.1.[1] The tubular portion of the shelter was made up of 8-ft sections of 90-in.-I.D. culvert pipe. Structures 601 and 602 were located in Area 3a and were used for shots 1 and 8. Structure 601 (see Fig. 3.1) consisted of a tubular main shelter section made up of six 8-in.-thick reinforced-concrete-culvert sections, each 8 ft long. The shelter was equipped with a double-entry ramp and a baffle-type vestibule. Structure 602 was similar except that three of the six culvert sections were made up of thick multiplate steel, and there was only a single-entry ramp leading into a vestibule not equipped with a baffle (see Fig. 3.2). Structure 7.9.1b was located in Area 7 and was used on shots 3, 4, and 11. This structure was used previously on Operation Buster-Jangle and is described in a report on that operation.[2] Its construction was generally similar to that of Structure 601 except that the double-ramp entry opened directly into the tubular portion of the shelter without an intervening vestibule (see Fig. 3.3). The soil overlay covering the concrete-culvert portion of the shelter was 3 ft thick, and that over the steel-pipe sections was 3 ft 8 in. thick.

On shot 8 a special shelter section was constructed to attempt to simulate the geometry of a shelter directly at Ground Zero. This structure, Building 613, consisted of a 12-ft section of multiplate steel culvert without ramps or entryways except for a trap door and tunnel which was filled with sandbags before the detonation (see Fig. 3.4). The center line of the culvert was at mean grade, and the earth was dug out from in front of the pipe section and piled over the upper portion of the pipe. The center of the culvert section "saw" the weapon through a minimum of 3 ft 8 in. of earth. The face of the earth overlay between the culvert and the weapon was normal to the radial line from the point of detonation. Over the top, back, and ends of the culvert the earth thickness was a minimum of 5 ft.

The orientation of all shelters with respect to Ground Zero is shown in Fig. 3.5.

3.2 ANIMAL-EXPOSURE EQUIPMENT

All animals exposed on Project 23.1 were confined in cubical containers, measuring 2 ft on a side. These units were mounted on angle-iron bases within the shelters along the wall nearest the point of detonation. The exact location of each unit on each detonation is given in Figs. 3.1 to 3.4. The units are identified by numbers, and a tabulation of the unit numbers and types and the types and number of experimental animals contained therein is given in Table 3.1.

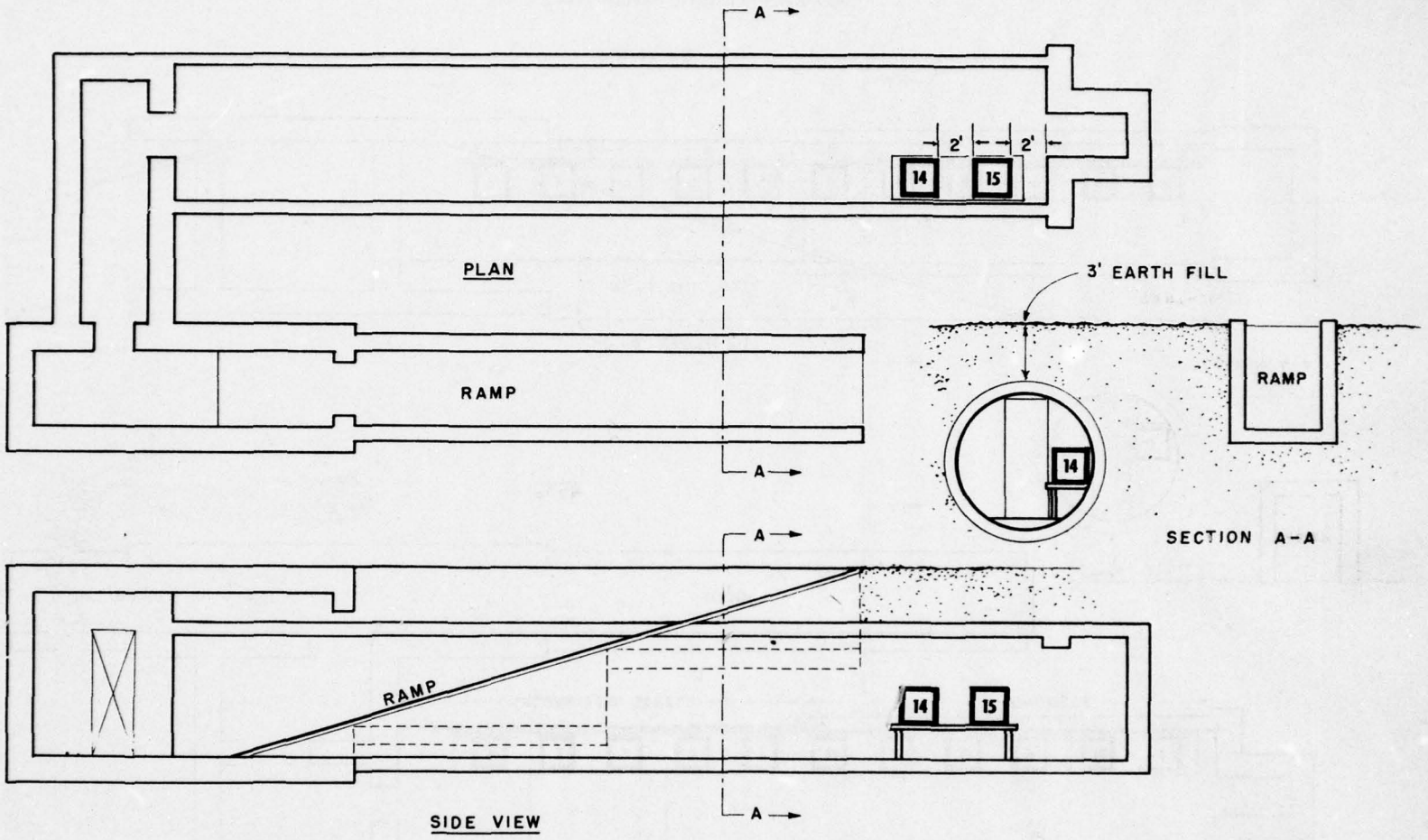

Fig. 3.1—Schematic drawing of Shelter 601.

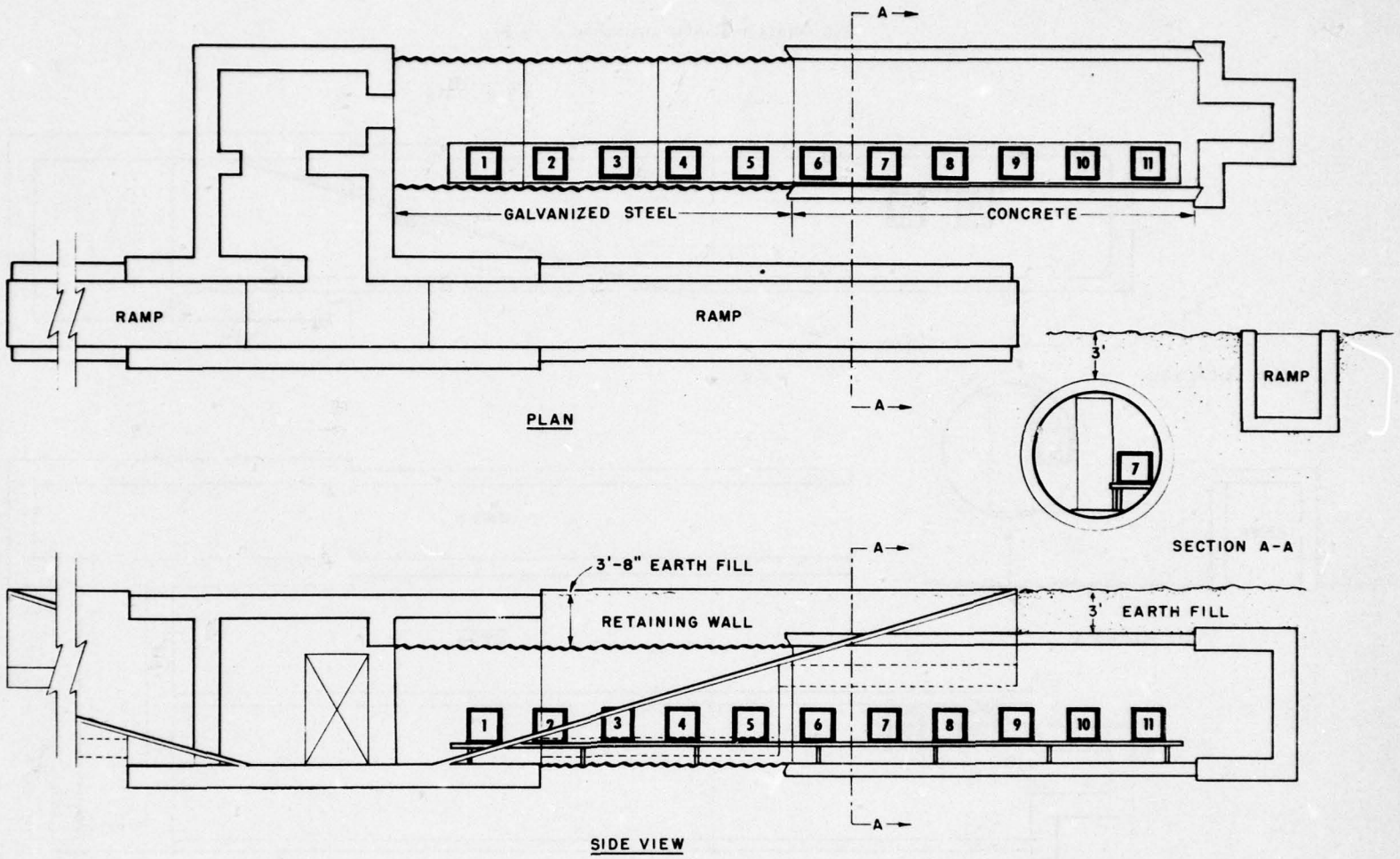

Fig. 3.2—Schematic drawing of Shelter 602.

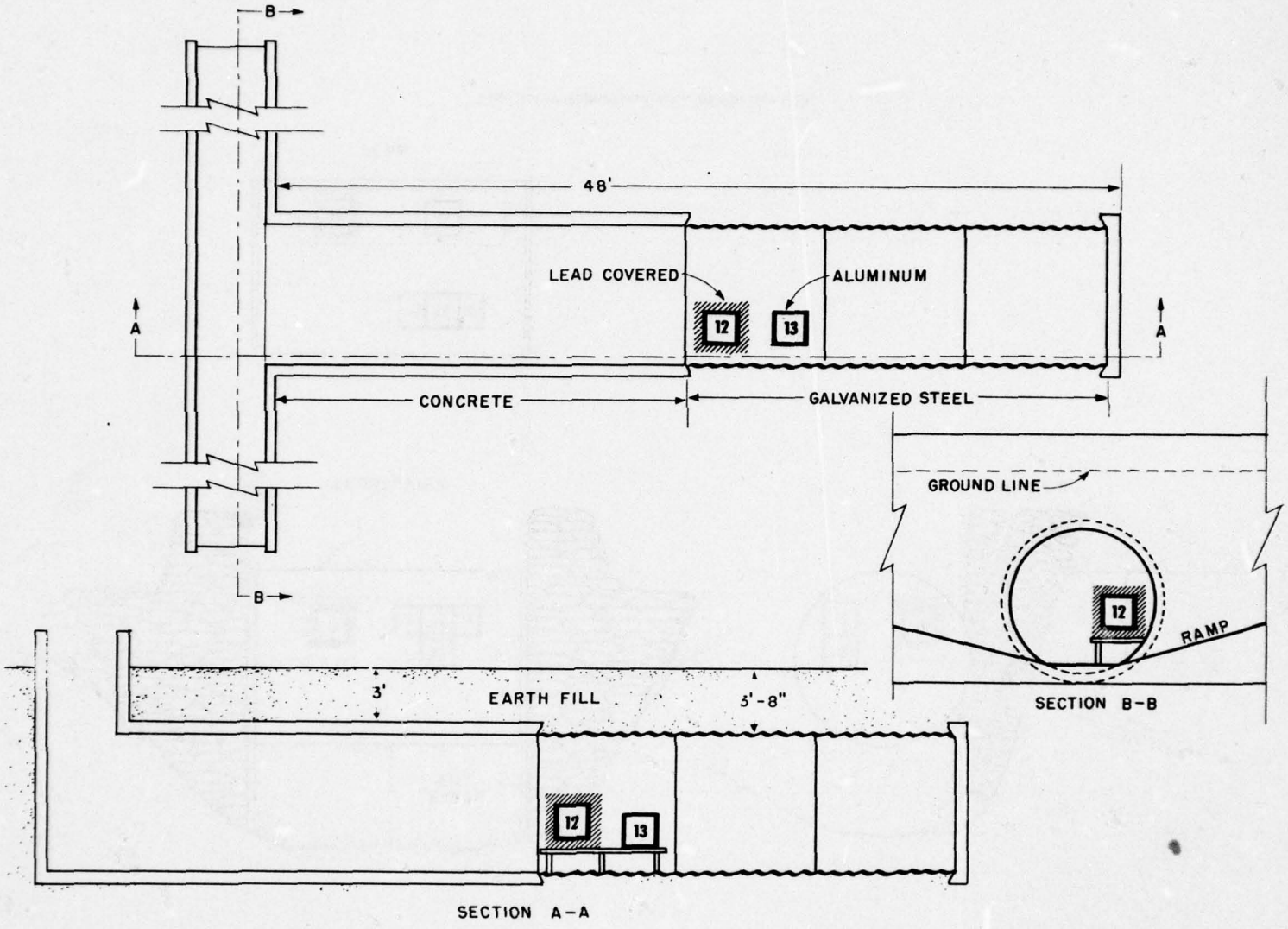

Fig. 3.3—Schematic drawing of Structure 7.9.1b.

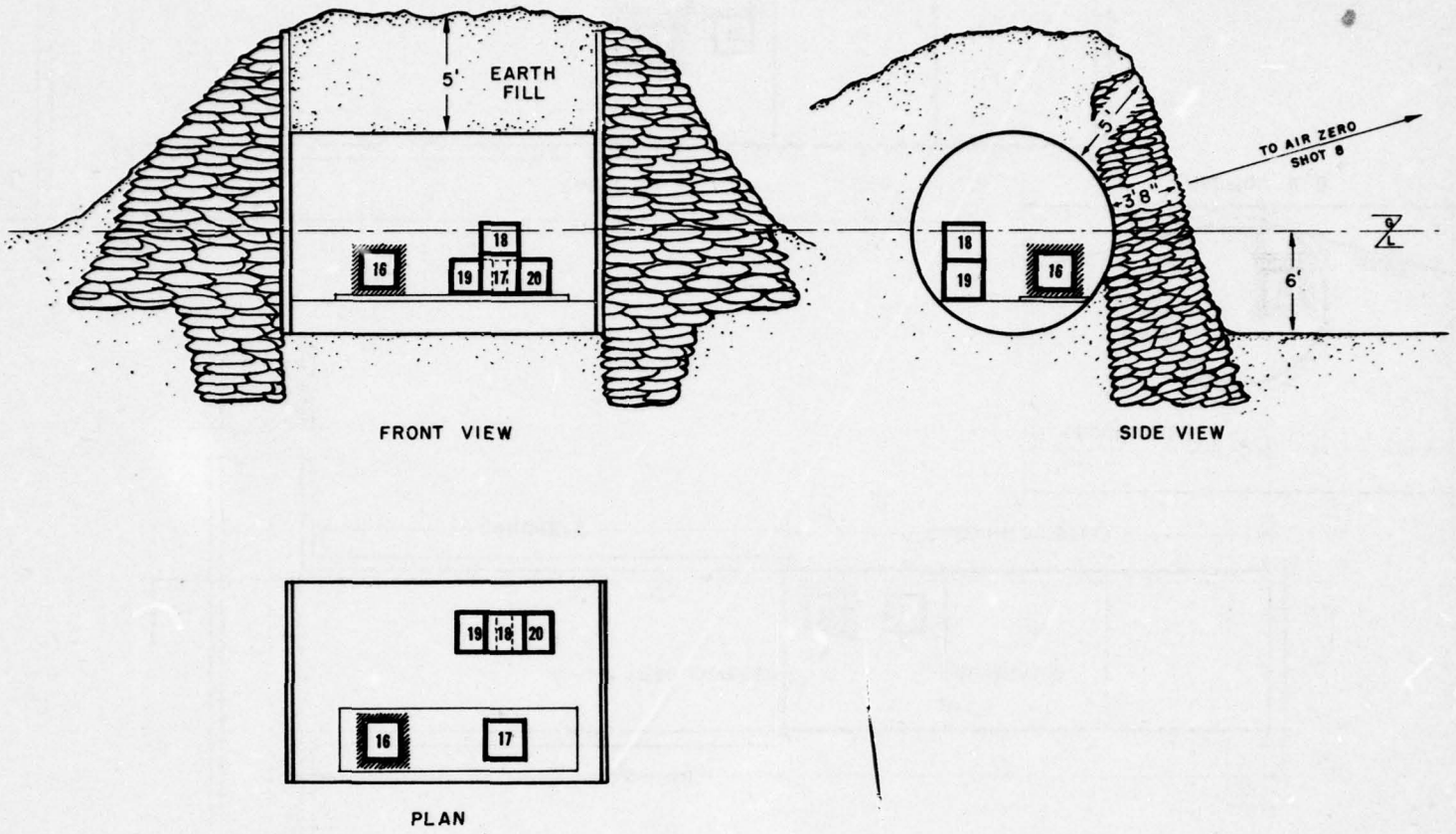

Fig. 3.4—Schematic view of Shelter 613.

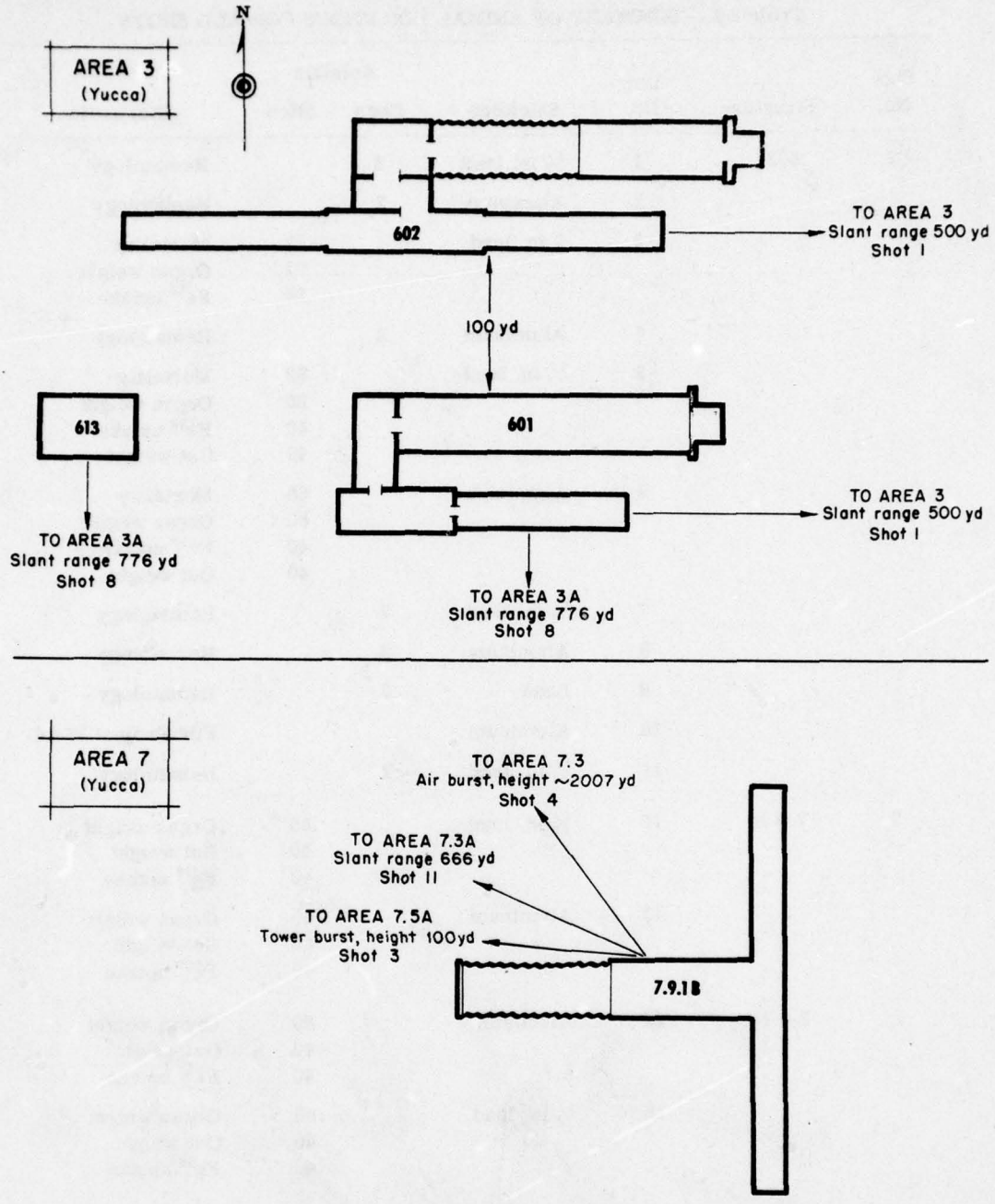

Fig. 3.5—Orientation of shelters with respect to site of detonation.

Table 3.1—SUMMARY OF ANIMAL LOCATIONS FOR ALL SHOTS

Shot No.	Structure	Unit No.	Shielding	Animals		Disposition
				Dogs	Mice	
1	602	1	½ in. lead	2		Hematology
		2	Aluminum	2		Hematology
		3	1 in. lead		72	Mortality
					72	Organ weight
					36	Fe^{59} uptake
		4	Aluminum	2		Hematology
		5	½ in. lead		80	Mortality
					80	Organ weight
					40	Fe^{59} uptake
					40	Gut weight
		6	Aluminum		80	Mortality
					80	Organ weight
					40	Fe^{59} uptake
					40	Gut weight
		7	½ in. lead	2		Hematology
		8	Aluminum	2		Hematology
		9	Lead	2		Hematology
		10	Aluminum			For Project 23.14
		11	½ in. lead	2		Hematology
3	7.9.1b	12	½ in. lead		80	Organ weight
					40	Gut weight
					40	Fe^{59} uptake
		13	Aluminum		80	Organ weight
					40	Gut weight
					40	Fe^{59} uptake
4	7.9.1b	12	Aluminum		80	Organ weight
					40	Gut weight
					40	Fe^{59} uptake
		13	½ in. lead		80	Organ weight
					40	Gut weight
					40	Fe^{59} uptake
8	601	14	½ in. lead		40	Organ weight
		15	Aluminum		40	Organ weight
	602	10	½ in. lead		40	Organ weight
		11	Aluminum		40	Organ weight

Table 3.1 — (Continued)

Shot No.	Structure	Unit No.	Shielding	Animals: Dogs	Animals: Mice	Disposition
	613	16	3 in. lead		40	Mortality
					40	Organ weight
					40	Gut weight
		17	Aluminum		40	Mortality
					40	Organ weight
					40	Gut weight
		18	Aluminum	2		Hematology
		19	Aluminum	2		Hematology
		20	Aluminum	2		Hematology
11	7.9.1b	12	4 in. lead	2	40	Dogs — hematology Mice — gut weight
		13	Aluminum	2	40	Dogs — hematology Mice — gut weight

Each cubical unit consisted of a light angle-iron frame covered with $\frac{1}{4}$-in. aluminum-sheet sides. A center partition of angle aluminum covered with wire cloth contained a heating element and divided the unit into two identical sides. When the units were used for dogs, one dog fitted into each side of a cube, and, when they were used for mice, 10 wire-mesh cages measuring 10 in. by 10 in. by 2 in. were fitted into each side of the unit. Details of construction of the cubical animal-exposure units can be seen in Fig. 3.6. The first photograph (A) in the figure is that of an aluminum cube mounted on the angle-iron support bench. The electrical boxes on top of the cube automatically controlled heating for each cube individually. Ventilation was provided by the small fans shown. The second picture (B) shows the same cube opened to show internal construction. One of the wire-mesh cages used for exposing the mice can be seen. The third photograph (C) shows an aluminum cube, with $\frac{1}{2}$ in. of lead added to all sides. The fourth picture (D) indicates the method of mounting the cubes in the shelters. These photographs were taken in Shelter 602 following shot 1, and the absence of damage to the cubes should be noted.

Certain of the units were covered with varying thicknesses of lead to shield out gamma radiation. In the majority of the shelters $\frac{1}{2}$-in.-thick lead sheets were placed over each side of the cube and were held in place by lugs welded to the angle-iron frame. All lead used was checked spectrographically and was determined to be free of any impurities with high capture cross sections for neutrons. Considerations of the effect of lead shielding on incident neutrons have been discussed elsewhere[3,4] and in general indicate that for lead thicknesses of $\frac{1}{2}$ in. no appreciable changes would have occurred in the incident neutron spectrum or flux. In two shelters on two of the shots the anticipated gamma flux was so high that the thickness of lead around certain cube units was increased to 3 to 4 in.

Each unit was equipped with a ventilating fan. Mean unit temperatures were remarkably constant at 75 ± 3°F regardless of ambient free-air or shelter-air temperatures.

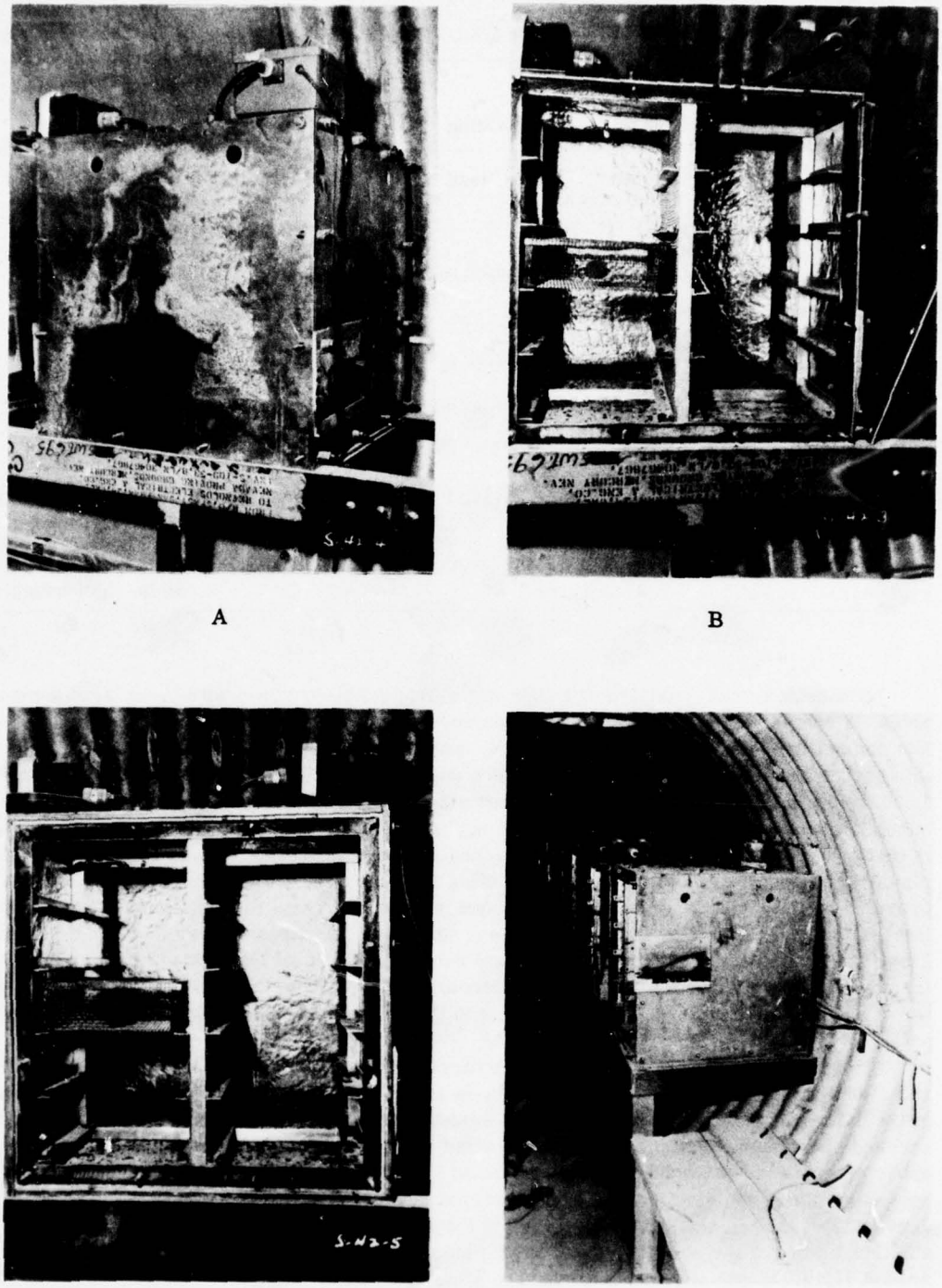

Fig. 3.6—Details of construction and mounting of cubical animal-exposure units.

3.3 PLACEMENT OF BIOLOGICAL MATERIAL

Mice were bred at the U. S. Naval Radiological Defense Laboratory (USNRDL) during the winter and spring of 1953. When animals had reached an age of approximately 5 weeks, they were transported by air to the Nevada Proving Grounds. At the test site the animals were held in an animal colony building. Upon arrival the mice were selected according to body weight by the method used for both the Greenhouse and Tumbler-Snapper biological experiments.[4,5] No attempt was made to select the animals according to age, since the age of each group received at the test site was quite constant (5 weeks plus or minus 1 week). Female animals destined for organ weight studies were caged in groups of 10 or 12 mice during the entire period of the experiments. Male animals destined for gut weight studies were also caged in groups of 10 or 12 mice; however, those male animals included for mortality studies were individually caged. During the selection and randomization procedures the animals were distributed into experimental groups of 10 animals each and were maintained in these groupings throughout the entire experimental period.

Before each shot, groups of animals were loaded into exposure cages (10 animals to the cage) approximately 12 hr before detonation time. Sections of oranges were placed in each cage to provide the animals with nourishment. Cages were transported to the field and were placed in exposure units approximately 8 hr before detonation time. After the explosion the animals were recovered as soon as conditions permitted and were returned to the animal colony and to their permanent holding cages. The average time between the detonation and the return of the animals to the colony building was about 5 hr.

Male animals for mortality observations were held at the proving grounds for the first 30 days after exposure. At the end of this time they were transported by air to USNRDL where they are being held for long-term studies.

3.4 CONTROL-STUDY X-IRRADIATION TECHNIQUES

All X-ray control studies on mice were carried out at the animal colony in Mercury, Nev., by means of a portable General Electric industrial X-ray unit housed in a motor van. The radiation factors used throughout were: 250 kvp; 8 ma; filter, 0.5 mm Cu plus 1 mm Al; HVL, 1.0 mm Cu; skin to target distance, 100 cm; dose rate, approximately 7.5 r/min as measured in air with a Victoreen r-meter; backscatter, 28 per cent of the air dose (difference between air dose and the reading in the same position with mice and scatter board in place). A maximum of 30 mice were irradiated simultaneously in individual, perforated lusteroid centrifuge tubes placed radially on a circular wooden turntable platform rotated at 3.5 rpm during exposure.

3.5 BIOLOGICAL PROCEDURES

3.5.1 General Considerations

Quantitative biological end points in the mouse used to assay the total biologically effective dose in the shelters included spleen-thymus weight reduction, white blood count decrease, mortality rate, decrease of radioactive-iron uptake in erythrocytes, and gut weight reduction. In order to quantify as accurately as possible the degree of effect seen, the magnitude of change in each of these end points as a function of X-ray dose was determined on the same strain of mice used in the shelters (see Sec. 3.4 for X-ray factors used). Adherence to the principles of pharmacological assay was attempted in that an X-ray machine was brought to the test site and, in so far as was possible, X-ray control studies were carried out on a random sample of animals comparable to those used for field studies, generally within a few days of bomb detonation.

The degree of change in any end point in mice exposed in the shelters, then, could be expressed as the dose of X radiation necessary to produce that magnitude of change in the strain of mouse used. This dose is termed "rem" (roentgen equivalent mammal). Therefore, the term "rem" as used in this report indicates the dose of 250-kvp X radiation required to produce the observed biological effect.

Observations on dogs included mortality, signs of illness, weight loss, temperature, and hematology. It was not feasible to carry out X-ray control studies on dogs at the test site. Responses observed in dogs exposed to high energy (1000 or 2000 kvp) X radiation at the Naval Medical Research Institute (NMRI) and at USNRDL were used to estimate the rem dose received by dogs exposed in the shelters.[6,7]

Details of biological procedures employed are given in Secs. 3.5.2 to 3.5.6.

3.5.2 Spleen-Thymus Weight Determinations

Female animals were used for determination of changes in the weight of the spleen and thymus. Details of the procedure have been reported elsewhere.[3,4,8] Briefly, exposed animals were sacrificed by decapitation 120 hr after exposure. The spleen was dissected free and weighed, with precautions against drying. The thymus of each animal was removed and fixed individually in 10 per cent formalin for 24 hr. At the end of the period of fixation, the adherent fat and connective tissue was dissected free, and the organ was blotted dry and weighed.

3.5.3 Hematological Observations

Peripheral blood counts were done on all mice sacrificed for organ weight determinations. Animals were weighed individually before sacrifice, were lightly anesthetized with ether, and were decapitated with a sharp scissors. Blood from the cervical stump was collected in a siliconed watch glass, and a white blood cell diluting pipette was filled directly. Smears of the fresh blood were also made. N/10 hydrochloric acid was used as the white cell diluting fluid, and the smears were stained with Wright's stain. One white cell pipette was used for each animal, and the cells in both sides of the counting chambers were enumerated. Filled pipettes were rotated on a Bryan-Garrey rotor for at least 10 min, with adequate precautions against drying, to ensure that proper settling of the cells had occurred. In differential counting, smears were examined until 100 cells had been observed or until the search for cells had continued for 10 min, whichever occurred first. Blood from the cervical stump also contained whatever thoracic duct lymph emerged during the process of decapitation.

Dogs were bled by introducing a 20-gauge hypodermic needle into the anterior foreleg vein and allowing the blood to drip from the end of the needle. The forelegs of the dogs were shaved before bleeding, and the skin was rubbed thoroughly with an acetone-soaked sponge before introduction of the needle. Pipettes were filled directly from the end of the needle. Two white blood cell pipettes were filled for each dog at each bleeding, and the blood was diluted 1 : 20 with 3 per cent acetic acid solution. When it was anticipated that the total white blood cell count would be low, dilutions of 1 : 10 were made to increase the number of cells enumerated on each animal. Pipettes were rotated 10 min on a Bryan-Garrey rotor, and both sides of a conventional counting chamber were filled from each diluting pipette. The cells on each side of each counting chamber were enumerated after a settling period of 10 min. Smears were examined until 100 cells were seen or until 10 min had passed, whichever occurred first.

3.5.4 Mortality Observations

Animals exposed for mortality observations were individually caged both before and after exposure. Animals were checked for deaths at least once a day during the first 30 days after exposure, and during the periods of peak incidence of deaths mortality was recorded as often as every 2 hr.

3.5.5 Radioactive-iron-uptake Determinations

Female mice were used for the determination of uptake of radioiron in erythrocytes. Exposed and control animals were injected (intraperitoneally) approximately 24 hr after exposure with 0.25 cc of a solution containing 0.1 microcurie of Fe^{59} as ferric chloride in 2N HCl buffered to pH 4 with saturated sodium citrate solution. Sacrifice by decapitation under ether anesthesia was carried out approximately 120 hr after exposure. Blood was collected and centrifuged in a heparinized constant-bore glass tube for hematocrit determination. Samples were returned to USNRDL for the determination of red cell activity. At USNRDL the entire glass tube was placed in the well of a scintillation counter and counted for a period of 3 min. The activity observed was reported as counts per 3 min per cc of packed red cells.

3.5.6 Gut Weight Determinations

Male animals were used for determination of changes in the weight of the intestinal tract. Exposed animals were sacrificed by decapitation under light ether anesthesia 48 hr after exposure. The entire small intestine was dissected free from the mesentery and severed at the pyloric sphincter and the ileocecal junction. It was then opened throughout its entire length and washed free of contents. When all gut contents had been removed, the intestine was placed in previously tared weighing pans and dried in an oven at 95°C for 24 hr. (This proved adequate to achieve constant weight.) The dried intestine and pan were then weighed, and the dry weight of the gut was calculated. The procedures were essentially those described by Conard.[9]

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CHAPTER 4

EXPERIMENTAL RESULTS

4.1 X-RAY CONTROL STUDIES ON MICE

4.1.1 Spleen-Thymus Weight Observations

Four separate X-ray control studies were conducted at the test site. The mean weights and their standard errors obtained from each experiment are summarized in Table 4.1. However, analysis of the control X-ray data was performed using the natural logarithm of the individual thymus or spleen weights, since preliminary considerations indicated that an equation of the form

$$y = y_0 e^{bx} \tag{4.1}$$

where y = thymus or spleen weight, X-irradiated animals
y_0 = thymus or spleen weight, unirradiated control animals
b = slope of the function
x = X-ray dose in roentgens

would describe adequately the relation between thymus or spleen weight and X-ray dose, and, in logarithmic form, would yield a straight line.

Table 4.1 — THYMUS AND SPLEEN WEIGHT DATA FOR X-RAY CONTROL STUDIES

Control experiment No.	Group or dose, r	Number of animals	Thymus		Spleen	
			Mean weight ± S.E.,* mg	Per cent of control	Mean weight ± S.E.,* mg	Per cent of control
1	Stressed controls	48	65.7 ± 2.4		111.4 ± 3.8	
	50	36	55.8 ± 2.7	84.9	80.5 ± 3.5	72.3
	150	36	44.5 ± 2.3	67.7	68.2 ± 3.8	61.2
	300	36	22.2 ± 1.1	33.8	42.4 ± 1.7	38.1
	500	36	11.2 ± 0.7	17.0	24.4 ± 1.0	21.9
	700	36	8.7 ± 0.5	13.2	23.1 ± 1.4	20.7

Table 4.1 — (Continued)

Control experiment No.	Group or dose, r	Number of animals	Thymus		Spleen	
			Mean weight ± S. E.,* mg	Per cent of control	Mean weight ± S.E.,* mg	Per cent of control
2	Stressed controls	24	79.2 ± 3.7		106.9 ± 4.6	
	25	24	71.4 ± 3.6	90.1	93.9 ± 3.9	87.8
	75	24	71.0 ± 4.3	89.6	87.0 ± 4.0	81.4
	100	24	56.4 ± 3.2	71.2	69.4 ± 4.6	64.9
	200	24	38.4 ± 2.2	48.4	61.8 ± 3.4	57.8
	400	24	22.6 ± 1.6	28.5	30.6 ± 1.3	28.6
3	Stressed controls	30	80.9 ± 4.7		108.0 ± 6.5	
	150	30	57.3 ± 3.2	70.8	69.8 ± 3.5	64.6
	250	30	31.5 ± 2.5	38.9	46.3 ± 2.9	42.9
	350	30	25.7 ± 1.5	31.8	35.8 ± 2.9	33.1
	600	30	10.0 ± 0.5	12.3	22.2 ± 1.3	20.5
	800	17	7.4 ± 0.4	9.1	14.5 ± 1.1	13.4
4	Stressed controls	30	78.5 ± 2.6		118.8 ± 3.6	
	100	30	50.8 ± 1.8	64.7	64.2 ± 2.6	54.0
	125	30	48.9 ± 2.5	62.2	63.4 ± 3.0	53.4
	175	30	44.6 ± 1.8	56.8	65.2 ± 2.6	54.9
	450	30	19.4 ± 1.1	24.7	30.7 ± 1.1	25.8

*S.E. = standard error.

The adequacy of this relation was tested using the analysis of variance. Each control study was considered separately, and a significant regression was found in each case with the exception of the first thymus study and the fourth spleen study, where deviation about the regression line was excessive. The slopes of the individual regression lines were then obtained, and a test for heterogeneity indicated that no significant difference among the slopes existed. Hence a weighted pooled estimate of the slopes was determined and found to be -2.9×10^{-3} for the spleen and -3.2×10^{-3} for the thymus (see Table 4.2).

The transformation employed proved adequate to describe the relation between organ weight and dose. In addition, the use of natural logarithms resulted in an essentially constant variance at all dose levels. This fact allowed easy fitting of least-square lines, since weighting was not necessary, and facilitated greatly the computations.

In order that approximate rem doses (see Sec. 3.5.1) corresponding to spleen or thymus weight loss seen following exposure of experimental mice in the field could be readily obtained, the curves shown in Figs. 4.1 and 4.2 were constructed such that the control value (y_0; 0 dose) corresponded to 100 per cent. (Since the ordinates in the figures are plotted as $\log_{10}$, the slopes in the figures must be divided by 0.4343 to obtain the values of the slope of the function given in Table 4.2.) Thus, if experimental thymus or spleen weights are expressed as per cent of their own control value, the approximate rem dose corresponding can be read easily from the graph. Actually, the values for rem were obtained analytically from Eq. 4.1.

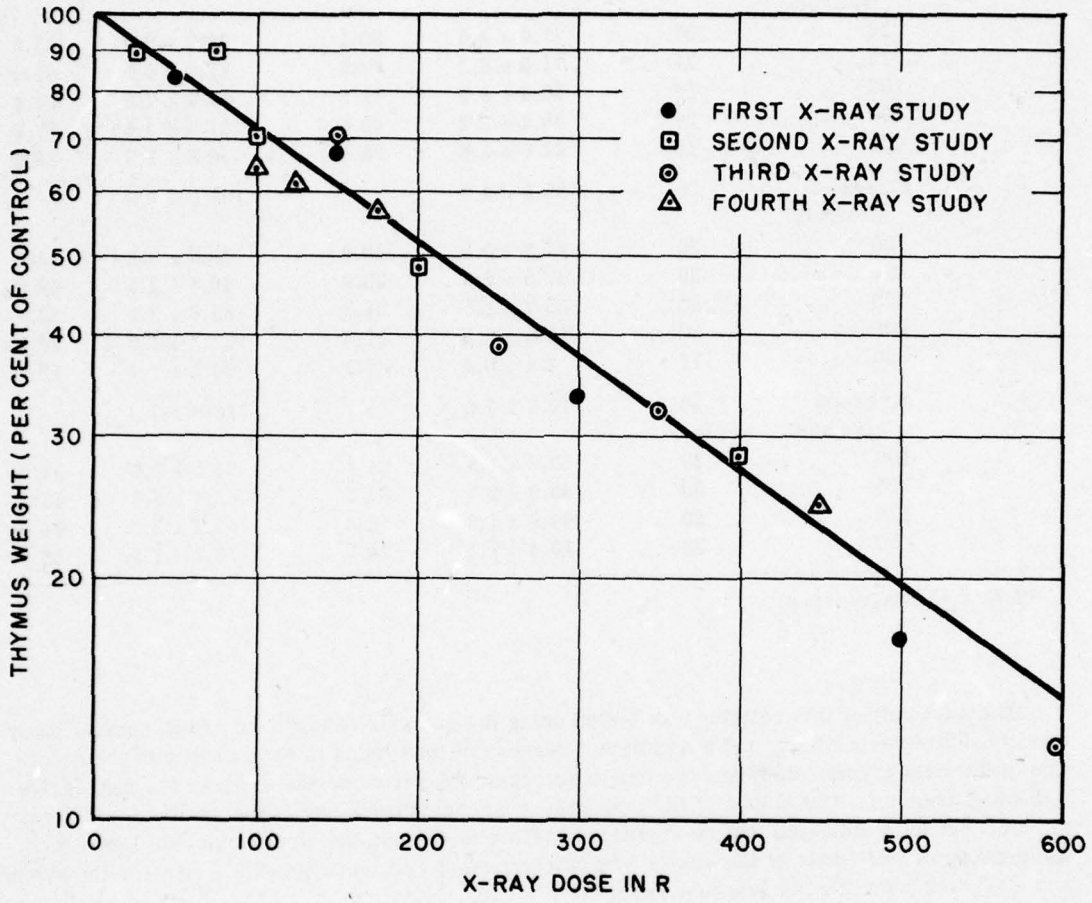

Fig. 4.1—Regression of thymus weight on X-ray dose.

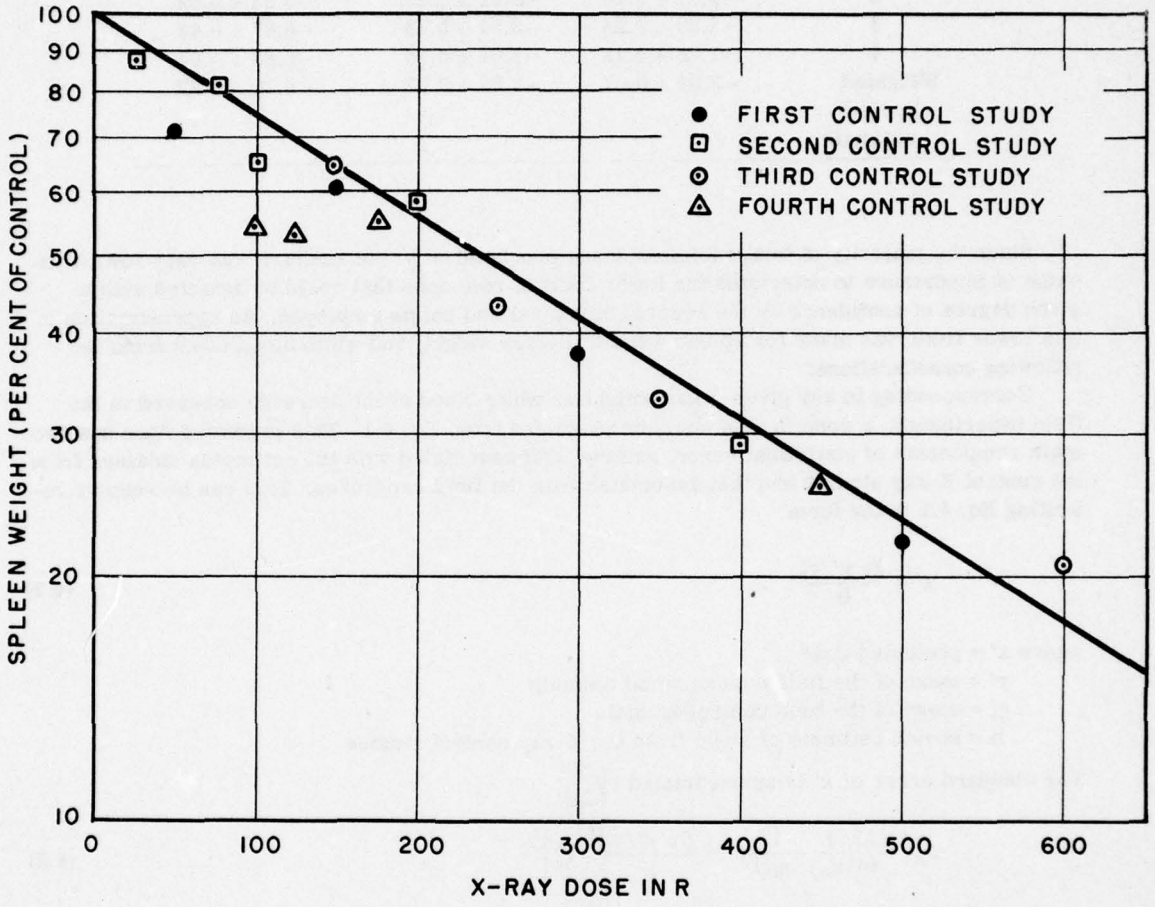

Fig. 4.2—Regression of spleen weight on X-ray dose.

Table 4.2—SLOPES OF REGRESSION LINES FOR SPLEEN, THYMUS, AND TOTAL WHITE BLOOD COUNT FOR X-RAY CONTROLS

Control study No.	Slope of regression lines ± S.E. ($\times 10^{-3}$)		
	Spleen	Thymus	White blood count
1	−2.93 ± 0.11	−3.15 ± 0.09	−6.99 ± 0.30
2	−3.03 ± 0.18	−3.31 ± 0.22	−5.33 ± 0.62
3	−3.29 ± 0.24	−3.54 ± 0.16	−6.87 ± 0.43
4	−2.70 ± 0.12	−3.04 ± 0.15	−6.83 ± 0.64
Weighted pooled estimate	−2.94 ± 0.07	−3.24 ± 0.02	−6.71 ± 0.22

Since the majority of total radiation doses encountered in the shelters was very low, it became of importance to determine the lower limit of rem dose that could be detected with a given degree of confidence by the several biological end points employed. An approximation of this lower limit was made for spleen weight, thymus weight, and white blood count from the following considerations:

Corresponding to any given organ weight or white blood count decrease observed in the field experiments, a dose in rem could be predicted from Eq. 4.1. This predicted dose has two main components of statistical error, namely, that associated with the estimates obtained from the control X-ray studies and that associated with the field exposures. This can be seen by rewriting Eq. 4.1 in the form

$$x' = \frac{\ln y'/y_0'}{b} \tag{4.2}$$

where x' = predicted dose
y' = mean of the field experimental animals
y_0' = mean of the field control animals
b = pooled estimate of slope from the X-ray control studies

The standard error of x' is approximated by

$$S_{x'} = \frac{1}{b}\left[\left(\frac{1}{n_e} + \frac{1}{n_c}\right) S^2 + \frac{(\ln y'/y_0')^2}{b^2} V_b\right]^{1/2} \tag{4.3}$$

where n_e = number of field experimental animals
n_c = number of field control animals
S^2 = pooled estimate of the variability of animals within the dose groups of the control X-ray studies
V_b = variance of the estimate of b

Using Eq. 4.3, the standard error of the predicted dose for various organ weight or white blood count decreases was determined both for $n_e = 40$, $n_c = 40$, and for $n_e = 80$, $n_c = 48$ (the two combinations of group sizes used in the field experiments). From these standard errors the corresponding 99 per cent confidence intervals were calculated, and that dose was found at which its 99 per cent confidence interval just embraced zero. This dose, taken as an estimate of the minimal detectable dose, is shown in Table 4.3 for the thymus, spleen, and white blood count.

Table 4.3 — MINIMUM DOSES DETECTABLE BIOLOGICALLY

Number of animals used	Minimum detectable dose (99% confidence), rem		
	Spleen	Thymus	White blood count
40 experimental 40 control	57	65	77
80 experimental 48 control	50	55	70

In previous field operations thymus data were represented by plotting the probit of the per cent decrease in thymus weight from that of control values against the log X-radiation dose and determining the best line of fit.[1-3] In order to allow easy comparison with results of previous operations (LAf_1 mice were used previously), the present X-ray control data have been treated in this fashion also. The resulting curve is shown in Fig. 4.3. The best line of fit to the composite data was found to be

$$w = -0.188 + 2.245 \times S_w = 0.159 \tag{4.4}$$

where w = empirical probit of per cent thymus weight loss
x = log dose in roentgens

4.1.2 Hematological Studies

Four separate control X-ray studies were carried out at the test site. Data are summarized in Table 4.4, and the regression on dose of the white blood count expressed as log per cent of the control value is shown in Fig. 4.4. The regression coefficient for each study and the weighted pooled coefficient are shown in Table 4.2. The method of analysis was identical with that used for the spleen-thymus data (see Sec. 4.1.1) with the exception that the data were truncated at 300 r. Above this dose the response no longer fitted the relation shown in Eq. 4.1.

Table 4.4 — MOUSE WHITE BLOOD COUNT DATA FOR X-RAY CONTROL STUDIES

Control experiment No.	Group or dose, r	Number of mice	White blood count	
			Mean ± S.E.	Per cent of control
1	Stressed controls	48	5541 ± 270	
	50	36	4081 ± 250	73.6
	150	36	1962 ± 150	35.4
	300	36	771 ± 70	14.0
	500	36	428 ± 36	7.7
	700	36	224 ± 28	4.0

Table 4.4 — (Continued)

Control experiment No.	Group or dose, r	Number of mice	White blood count	
			Mean ± S.E.	Per cent of control
2	Stressed controls	24	4340 ± 383	
	25	24	3746 ± 410	86.3
	75	24	4167 ± 507	96.0
	100	24	2783 ± 242	64.1
	200	24	1481 ± 111	34.1
	400	24	594 ± 71	13.7
3	Stressed controls	30	3980 ± 257	
	150	30	919 ± 67	23.1
	250	30	773 ± 56	19.4
	350	30	262 ± 25	6.6
	600	30	100 ± 14	2.5
4	Stressed controls	30	4879 ± 418	
	100	30	2798 ± 142	57.4
	125	30	1855 ± 129	38.0
	175	30	1472 ± 92	30.2
	450	30	388 ± 41	7.9

4.1.3 Mortality Observations

Two mortality rate determinations were made at the site. Irradiations were done on 13 March and 12 May, respectively. Doses in the first study were excessive, and only one point in the lethal range was obtained. The second study resulted in five points in the lethal range. Analysis of these data by the approximate method quoted by Bliss[4] yielded an LD_{50} value of 475 r with a standard error of 9 r. The data are presented in Table 4.5, and the regression of mortality rate (expressed in probits) on X-ray dose is given in Fig. 4.5.

Table 4.5 — MOUSE MORTALITY DATA FOR X-RAY CONTROL STUDY

Control experiment No.	Number of mice	Dose, r	Per cent mortality	Mean survival time, days
1	36	Stressed controls	0.0	
	36	550	95	12.0
	36	650	100	8.7
	36	700	100	6.9
	36	750	100	5.7
	36	850	100	6.1

Table 4.5 — (Continued)

Control experiment No.	Number of mice	Dose, r	Per cent mortality	Mean survival time, days
2	30	400	13.3	13.5
	30	450	56.7	15.0
	30	500	60.0	14.2
	30	550	87.0	12.2
	30	600	93.3	10.6

Mean survival times for mice dying at all dose levels employed are presented in Table 4.5. Only at the LD_{100} and above did an appreciable number of mice die before the 8th or 9th post-irradiation day. At all dose levels greater than the LD_{100} the plot of number dying vs postirradiation day showed a bimodal pattern, with peaks of mortality on approximately days 4 and 11. These observations confirm findings in X-ray control studies carried out in connection with Operations Greenhouse[5,6] and Tumbler-Snapper.[3]

4.1.4 Radioactive-iron-uptake Studies

Two X-ray control studies on female mice were carried out at the test site (13 March and 1 April). The data obtained are tabulated in Table 4.6, and a plot of iron uptake in erythropoietic tissue vs X-ray dose is shown in Fig. 4.6. The discrepancy between the first and second series may be due to the fact that exposure of the stressed controls in the second study occurred after irradiation was complete, when temperature conditions were unfavorable. If the value obtained for the 10-r group is used as control instead of the unusually low value obtained with the stressed animals, the points obtained with the second series fall very close to the curve obtained with the first study.

Table 4.6 — IRON-UPTAKE DATA FOR X-RAY CONTROL STUDIES

Control experiment No.	Group or dose, r	Number of mice	Counts/3 min/cc ± S.E.	Per cent of control
1	Stressed controls	34	127,761 ± 6350	100
	25	22	106,559 ± 6420	83
	50	21	82,329 ± 5780	64
	100	24	49,112 ± 4910	38
	200	22	20,630 ± 2060	16
2	Stressed controls	24	81,229 ± 9	100
	10	23	103,404 ± 8	127
	25	23	86,733 ± 10	107
	75	24	54,042 ± 12	67

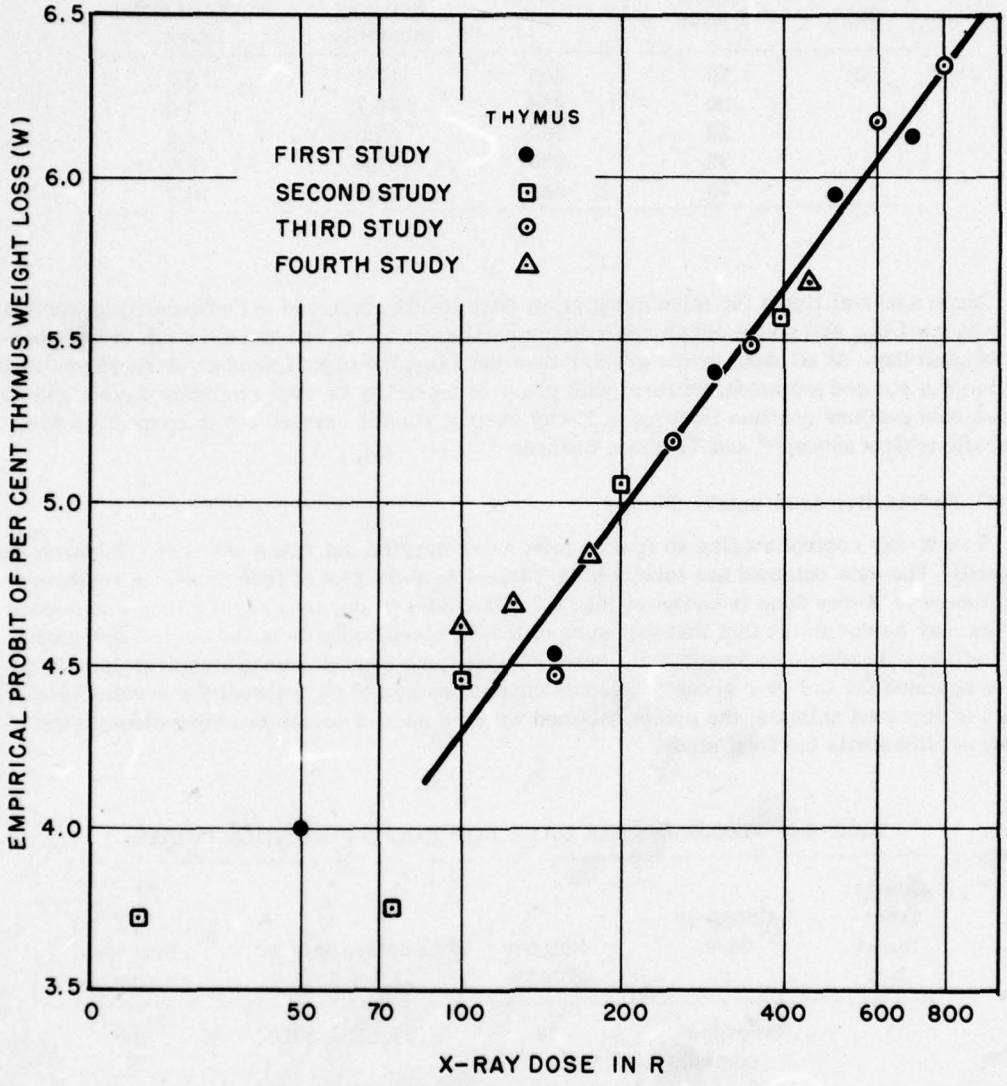

Fig. 4.3—Probit of thymus weight loss vs log X-ray dose.

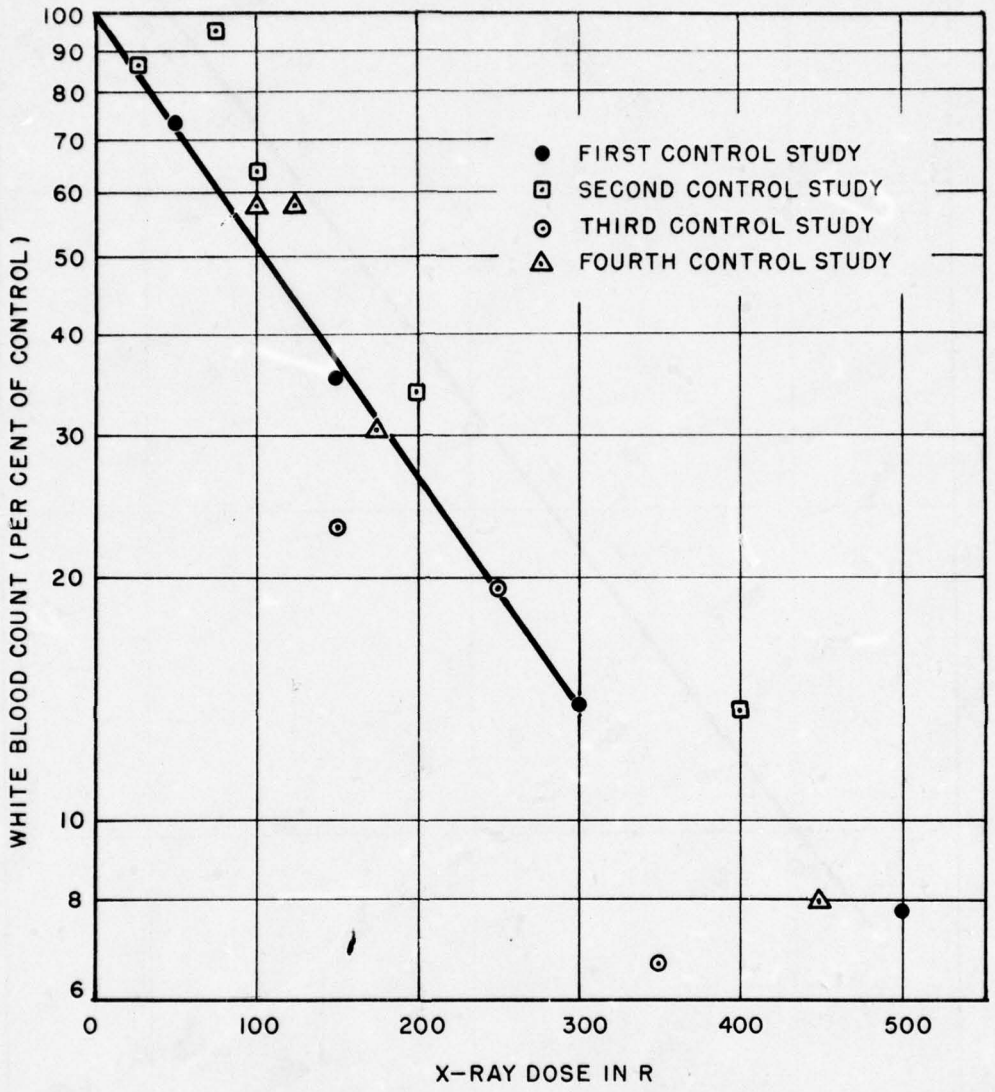

Fig. 4.4—Regression of white blood count on X-ray dose.

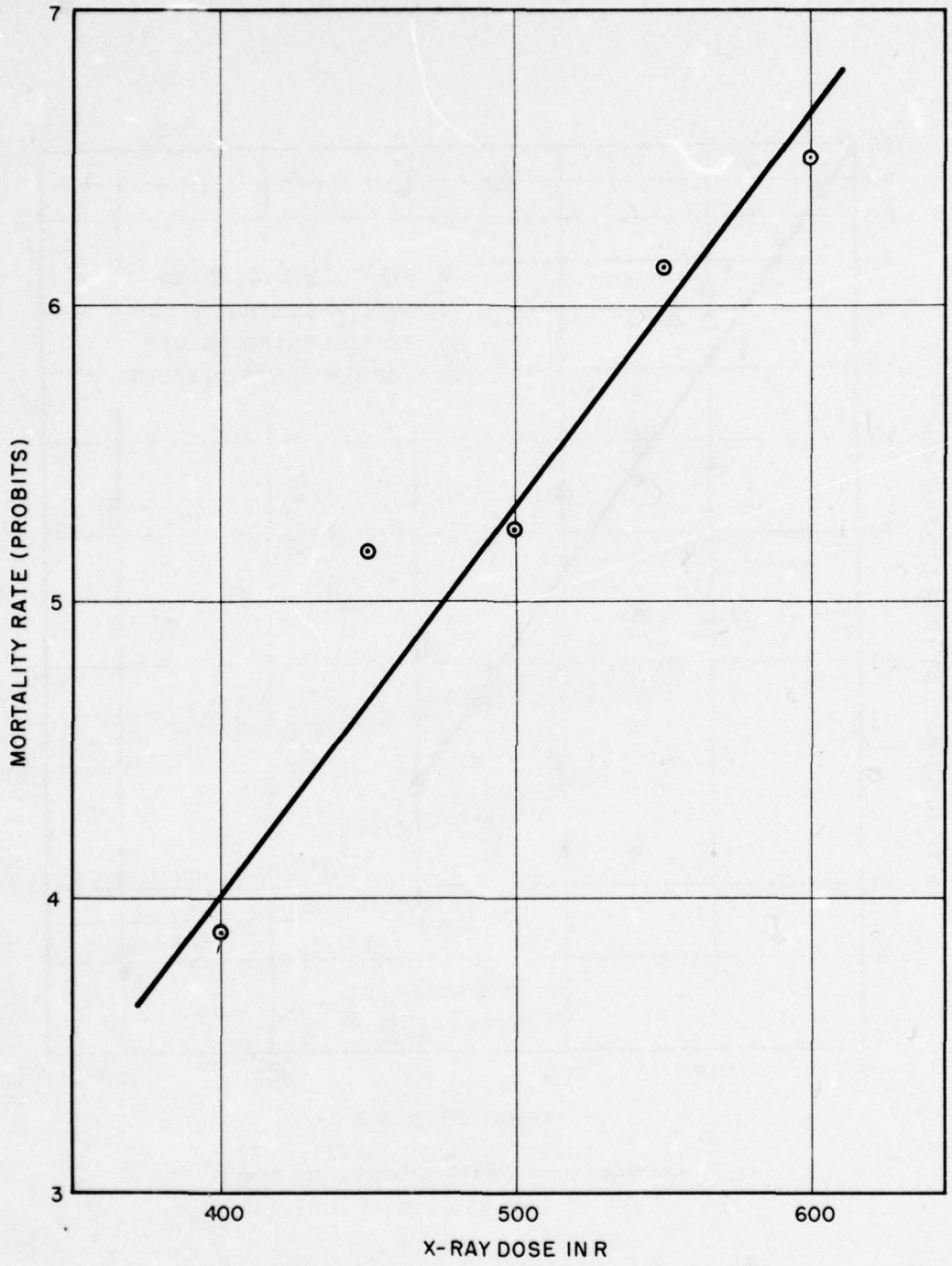

Fig. 4.5—Regression of mortality rate on X-ray dose.

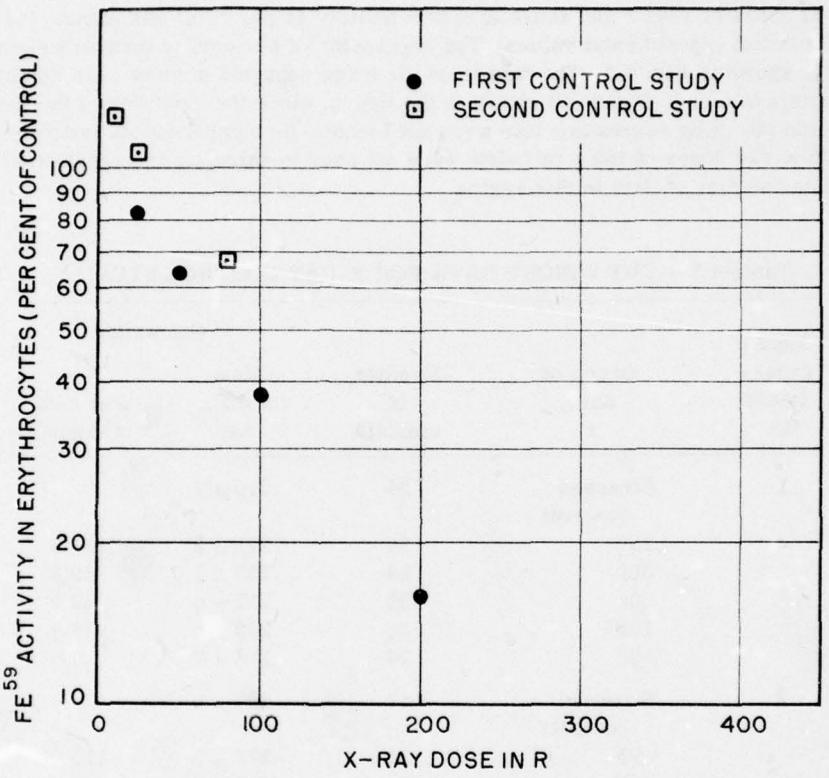

Fig. 4.6—Regression of Fe^{59} activity in erythrocytes on X-ray dose.

Since mice exposed for determination of radioactive-iron uptake in shots 1, 3, and 4 showed no significant difference between experimental and field stressed control animals, a statistical treatment of the X-ray control regression of iron uptake on dose was not necessary for evaluation of the field results.

4.1.5 Gut Weight Studies

Three separate X-ray studies on gut weight were performed at the test site (irradiated 14 March, 24 March, and 25 April). Results of these studies are listed in Table 4.7. Per cent of control gut weight was calculated after 56 per cent of the appropriate control value (maximum weight loss at doses of 1000 r and above is approximately 44 per cent) was subtracted from both the control and experimental values. The regression of per cent of control weight on X-ray dose is shown in Fig. 4.7. The data from the three separate studies were combined and used to calculate the least-square fit shown in the figure, since the deviation of the individual points from the resulting regression line were not found to be significant statistically. Values obtained with X-ray doses of 100 r or below were not used to calculate the regression line because of excess scatter of data in this region.

Table 4.7—GUT WEIGHT DATA FOR X-RAY CONTROL STUDIES

Control experiment No.	Group or dose, r	Number of animals	Gut weight	
			Mean ± S.E., mg	Per cent of control
1	Stressed controls	24	296 ± 7	
	150	24	271 ± 2	81.3
	300	24	256 ± 7	69.3
	600	22	215 ± 6	38.2
	750	24	203 ± 6	28.4
	900	24	178 ± 7	9.5
2	Stressed controls	24	265 ± 8	
	25	24	277 ± 7	110
	75	24	257 ± 8	93.4
	100	24	267 ± 7	102
	250	23	249 ± 7	86.1
	450	24	208 ± 4	51.4
3	Stressed controls	30	285 ± 7	
	200	30	261 ± 6	80.7
	400	30	228 ± 5	54.1
	600	30	204 ± 5	35.0
	800	30	188 ± 5	22.5

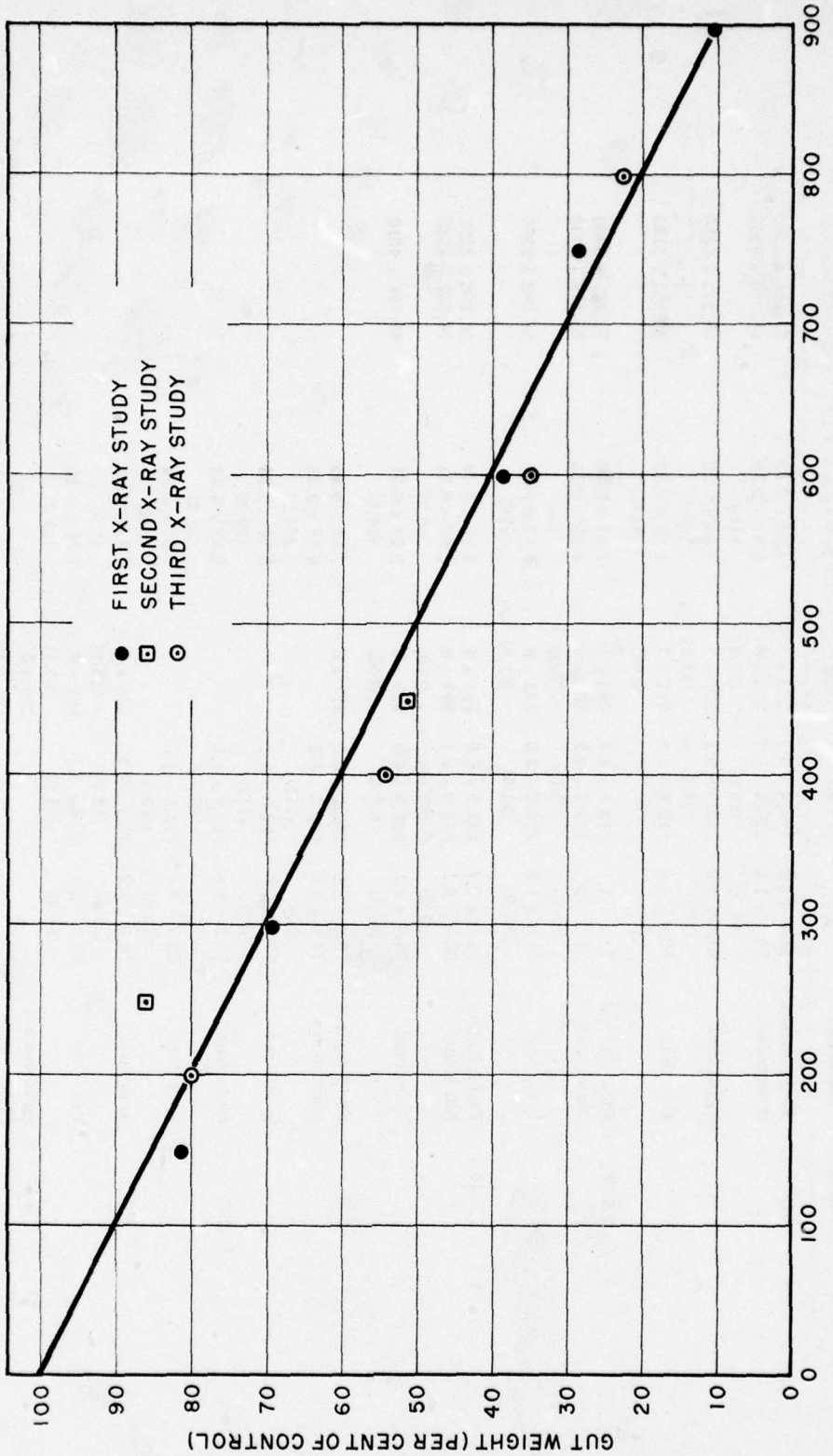

Fig. 4.7—Regression of gut weight loss on X-ray dose.

Table 4.8 — DATA ON MICE PLACED IN THE AEC COMMUNAL SHELTERS

Shot No.	Shelter	Container	Mean values ± S.E. Thymus, mg	Spleen, mg	Gut, mg	White blood count × 10^3	Fe uptake, counts/3 min/cc × 10^6
1	602	Field control	56.5 ± 2.0	124.4 ± 4.7	303 ± 5	4.98 ± 0.28	94,560 ± 8500
		Aluminum	54.5 ± 1.8	115.4 ± 2.7	294 ± 6	5.45 ± 0.30	88,078 ± 5300
			(96.5)	(92.8)	(93.2)	(109)	
		½ in. lead	61.5 ± 1.9	112.4 ± 3.2	294 ± 7	4.93 ± 0.20	87,372 ± 5210
			(109)	(90.4)	(93.2)	(99.1)	
		1 in. lead	58.9 ± 1.8	112.8 ± 3.3	311 ± 7	5.83 ± 0.27	88,287 ± 6120
			(104)	(90.7)	(106)	(117)	
3	7.9.1b	Field control	73.1 ± 3.1	119.4 ± 4.3	296 ± 5	3.77 ± 0.26	76,997 ± 5400
		Aluminum	70 ± 1.9	113.4 ± 3.3	300 ± 6	4.00 ± 0.25	78,315 ± 4700
			(95.6)	(95.0)	(103)	(104)	
		½ in. lead	61.4 ± 1.8	106.0 ± 3.0	293 ± 6	5.13 ± 0.26	83,982 ± 3350
			(83.9)	(94.5)	(97.8)	(136)	
4	7.9.1b	Field control	72.5 ± 2.7	154.7 ± 5.5	281 ± 4	5.95 ± 0.38	56,266 ± 3350
		Aluminum	68.4 ± 2.1	143.8 ± 4.1	293 ± 5	5.09 ± 0.21	76,482 ± 4580
			(93.3)	(93.4)	(110)	(85.7)	
		½ in. lead	69.7 ± 2.1	136.9 ± 4.5	286 ± 5	5.24 ± 0.21	66,994 ± 4010
			(96.1)	(88.5)	(104)	(86.1)	
8	601	Field control	75.0 ± 3.0	107.8 ± 4.9	317 ± 6	7.18 ± 0.52	
		Aluminum	77.9 ± 2.9	122.2 ± 3.9		5.38 ± 0.35	
			(104)	(113)		(74.9)	
		½ in. lead	77.0 ± 3.0	120.5 ± 5.1		5.22 ± 0.24	
			(103)	(112)		(72.7)	
	602	Aluminum	76.3 ± 3.8	110.6 ± 4.2		5.42 ± 0.32	
			(102)	(103)		(75.5)	
		½ in. lead	65.7 ± 3.1	113.5 ± 4.5		7.35 ± 0.59	
			(87.6)	(105)		(102)	
	613	Aluminum	18.3 ± 1.7	34.5 ± 1.5	196 ± 5	0.40 ± 0.04	
			(24.4)	(32.0)	(13.6)	(5.5)	
		3 in. lead	63.3 ± 2.7	91.6 ± 3.1	309 ± 6	3.04 ± 0.26	
			(84.4)	(85.0)	(94.5)	(42.3)	
11	7.9.1b	Field control			290 ± 6		
		Aluminum			197 ± 10		
					(28.2)		
		4 in. lead			276 ± 7		
					(89.0)		

4.2 FIELD STUDIES—BIOLOGICAL MEASUREMENTS

4.2.1 Shot 1

The mean values for all data on mice exposed in the communal shelters are shown in Table 4.8. Below each value, in parentheses, is given the mean expressed as per cent of the appropriate control value. The estimated rem doses received in each situation, as indicated by the several end points employed, are listed in Table 4.9.

Table 4.9—DOSES IN REM WITHIN AEC COMMUNAL SHELTERS

Shot No.	Shelter	Container	Estimated dose, rem*				
			Thymus	Spleen	Gut	White blood count	Fe uptake
1	602	Aluminum	0	< 50(25)	< 100	0	0
		½ in. lead	0	< 50(34)	< 100	0	0
		1 in. lead	0	< 50(34)	< 100	0	0
		Al dog				< 50	
		½ in. Pb dog				< 50	
3	7.9.1b	Aluminum	0	0	< 100	0	0
		½ in. lead	< 55(54)	< 50(39)	< 100	0	0
4	7.9.1b	Aluminum	0	< 50(25)	< 100	< 70(23)	0
		½ in. lead	0	< 50(41)	< 100	< 70(19)	0
8	601	Aluminum	0	0		< 70(43)	
		½ in. lead	0	0		< 70(47)	
	602	Aluminum	0	0		< 70(42)	
		½ in. lead	< 65(41)	0		0	
	613	Aluminum	435 ± 25†	387 ± 24	875	> 300	
		3 in. lead	< 65(52)	< 57(55)		128 ± 23	
		Al dog				> 600	
11	7.9.1b	Aluminum			730		
		4 in. lead			110		
		Al dog				> 600	
		4 in. Pb dog				< 100	

*See text, Sec. 4.2.1.
† Estimated dose ± S.E.

The rem doses were determined as follows: the decrease in mean value observed between a mean value and its appropriate control was tested for significance. If no significant difference (1 per cent level) was found, the dose for that situation was reported as 0 rem.

The minimum dose that could be detected with 99 per cent confidence under the conditions employed in the field has been estimated for the spleen, thymus, and white blood count end points (see Sec. 4.1.1). Values obtained in the field differing significantly from the appropriate control, and less than the estimated minimal detectable dose, are so reported. However, the analytical values obtained from Eq. 4.1 are also given in parentheses. Where values above the minimum detectable dose were obtained, the dose was estimated analytically and its standard

error was determined.

Because gut weights scattered excessively in the region below 100 r and thus were not used in calculating the regression of gut weight on X-ray dose, gut weights from field-exposed animals falling in this region were reported as being less than 100, and no extrapolation of rem dose was attempted. No values for radioactive-iron uptake in field-exposed animals differed significantly from the corresponding controls; hence all values for this end point are reported as indicating zero dose.

All biological end points obtained on mice exposed in shot 1 were consistent in that either a minimal or no difference was seen between control and exposed group values. There was no difference observed between animals exposed in aluminum cubes or in lead-covered cubes. The results are consistent with total radiation levels (gamma plus neutrons) of well below 50 rem.

Data obtained on dogs exposed in Shelter 602, shot 1, are presented in Table 4.10. No significant differences between the control and irradiated groups were obtained. However, the small loss of body weight, and particularly the slight but consistent reduction in white blood count, granulocytes, and mononuclear cells in both exposed groups, and of platelets in the aluminum-exposed groups, are suggestive. As was the case with the mice, the data are consistent with exposure to radiation levels of below 50 rem.

Table 4.10—DATA ON DOGS EXPOSED IN SHELTER 602, SHOT 1

Container	Post-irradiation day	Mean values* Weight, lb	Temp., °F	White blood count	Abs. poly	Abs. mono	Platelets
Control	−1	25.7	101.3	13,440	9,500	3,970	481,100
	1	25.6	101.2	13,743	9,760	3,990	414,300
	3	25.5	101.3	13,150	9,460	3,700	479,300
	6	25.1	101.4	10,900	6,960	3,980	532,860
	8	25.5	101.0	13,990	10,480	3,510	552,860
Aluminum	−1	25.2	101.7	14,600	9,940	4,660	365,000
	1	24.8	101.7	13,450	8,680	4,780	385,800
	3	24.2	101.1	11,900	7,280	4,620	445,830
	6	24.2	101.7	10,615	7,560	3,060	429,170
	8	24.1	101.1	9,325	6,370	2,960	330,000
Lead	−1	26.7	101.3	14,030	9,747	4,280	343,130
	1	25.8	101.4	10,660	7,490	3,170	370,630
	3	25.3	101.6	11,540	7,530	4,012	425,200
	6	25.5	101.7	9,153	6,420	2,740	397,500
	8	25.0	101.0	9,125	6,045	3,080	412,860

*Seven control animals; 6 animals in aluminum container; 8 animals in lead container.

4.2.2 Shots 3 and 4

Data obtained from mice exposed in shots 3 and 4 are presented in Table 4.8, and corresponding rem values for each end point studied are shown in Table 4.9. All end points indicated that minimal radiation levels existed within the shelter and certainly that the dose delivered was below 50 rem.

4.2.3 Shot 8

Mean values for all end points obtained with mice exposed in Shelters 601, 602, and 613 are tabulated in Table 4.8. Corresponding rem values are indicated in Table 4.9.

In Shelters 601 and 602 all end points indicated minimal exposure, which was certainly below 50 rem.

In Shelter 613 the mice in the aluminum container gave evidence of having received fairly massive doses of radiation. The spleen, thymus, and white blood count dose levels, all of which were determined on the same group of mice, indicated fairly consistent values of 387, 435, and greater than 300 rem, respectively. The mice exposed for gut weight determination, however, yielded a quite different rem value of approximately 875. The exposure of mice in the aluminum cube for mortality observation resulted in a 30-day mortality rate of 18 per cent and a mean survival time of 12.3 days for those dying. These lethality results and survival-time data are consistent with exposure to approximately 400 rem of predominantly gamma radiation. These differences between gut weight and other end points undoubtedly resulted chiefly from the marked gradient of dose level throughout the shelter structure resulting chiefly from partial removal of the earth covering by the blast wave (see discussion, Sec. 5.3). The damage to the shelter and the exposure of a portion of the metal culvert by the blast wave are shown in Fig. 4.8.

Spleen and thymus weights on mice exposed within the lead-protected cube were significantly different from control values and indicated doses slightly below the minimal detectable levels (57 and 65 rem for the spleen and thymus, respectively). The white blood count indicated a dose of 128 rem. These findings are consistent with low-level neutron exposure, as will be indicated in the discussion (see Sec. 5.3).

Dogs exposed in aluminum containers, Shelter 613, presented a picture consistent with massive exposure to penetrating radiation. Two animals exposed in an aluminum cube placed on top of the lower containers (see Fig. 3.4) had vomited before recovery. One of the four dogs placed in the lower containers vomited during recovery approximately 2 hr after exposure. The two dogs in the upper cube died on the third postirradiation day. The third dog that vomited gave evidence of diarrhea and retching on the third day and had expired by the fourth day. The remaining three animals were dead by the fifth day. Total white counts fell from a preirradiation mean of 14,600 to 10,000 the first day, 4100 the second, 6500 the third, and 208 (three survivors) on the fourth postirradiation day.

The sequence of events observed in the exposed dogs was consistent with exposure in excess of 600 r in the dogs in the lower cubicles and certainly in excess of 1000 r in the dogs in the upper cubicle.

4.2.4 Shot 11

Data on mice exposed in aluminum and lead cubes are listed in Table 4.8, and corresponding rem values are given in Table 4.9. The gut weights for the control animals in this series were remarkably low (233 mg as compared to the usual 280 mg) and were considerably lower than the gut weights of mice exposed in the lead cube. No explanation for the low control values was apparent. If the means of all control gut weights in the test series are used as control values, the dose within the aluminum cube becomes approximately 730 rem, and the dose within the lead cube is approximately 110 rem. These values are consistent with results obtained with the exposed dogs (see below).

Hematological studies obtained on the four dogs exposed in shot 11 are given in Table 4.11. The two animals placed in the aluminum container evidenced a precipitous drop in white blood count from preexposure levels of about 10,000 to less than 2000 on the third postirradiation day. Since this picture is indicative of exposure in excess of 600 rem (100 per cent mortality) and since all personnel were departing from the site, these animals were sacrificed on the fourth day. Dogs exposed in the lead containers evidenced a drop in white blood count from about 10,000 to about 7500 on the third postirradiation day. No change in differential count was present. These changes are consistent with exposure of 100 rem or below.

Fig. 4.8—View of Shelter 613 after shot 8, showing partial removal of the earth covering by the blast wave.

Table 4.11 — HEMATOLOGICAL DATA ON DOGS EXPOSED ON SHOT 11

Exposure container	Time*	White blood count Dog 1	Dog 2	Exposure container	Time*	White blood count Dog 3	Dog 4
Aluminum	D – 6	10,000	7,350	Lead	D – 6	10,400	17,600
	D – 5	10,400	13,800		D – 5	16,400	11,950
	D + 1	8,900	6,900		D + 1	7,100	9,200
	D + 2	10,900	5,950		D + 2	6,300	5,500
	D + 3	1,800	1,600		D + 3	7,300	8,300

*Day pre- or postexposure.

4.3 FIELD STUDIES — SUMMARY OF PHYSICAL MEASUREMENTS

A summary of the physical measurements which were considered pertinent to the biological studies and which were made in or near animal-exposure units follows. The Civil Effects Test Group reports dealing with these measurements should be consulted for further details.

4.3.1 Shot 1, Shelter 602

Gamma measurements: All readings of NBS film packs placed within Shelter 602, within the exposure cubes and free in the shelter, read below 15 r. Tissue-equivalent chambers (Rossi) indicated a total rep dose of 21.5 in Shelter 602. From data obtained in Shelter 601, approximately 3 rep of this may have resulted from neutron exposure.

Neutron measurements: Sulfur neutron readings all were below 10^7 n/cm^2. Gold neutron readings were approximately 4×10^7 n/cm^2. The manganese flux was 1.3×10^7 n/cm^2.

4.3.2 Shots 3 and 4

Gamma measurements: NBS film readings were not available at the time this report was written.

Neutron measurements: The sulfur flux was less than 10^7 n/cm^2. The gold flux was less than 3×10^7 n/cm^2.

4.3.3 Shot 8, Shelters 601 and 602

Gamma measurements: NBS readings indicated doses below 1.5 r.

Neutron measurements: The sulfur flux was less than 10^7 n/cm^2. The gold flux was less than 2×10^7 n/cm^2.

4.3.4 Shot 8, Shelter 613

Gamma measurements: Gamma measurements were made with NBS film packs and with the University of California at Los Angeles (UCLA) chemical dosimeters. These results, with the location of the dosimeters, are given in Fig. 4.9.

Neutron measurements: All sulfur flux readings, in the shelter and within the aluminum and lead cubes, were below 10^7 n/cm^2. The gold flux was approximately 3×10^{10} n/cm^2. The manganese flux (from about 0.4 to 3 Mev neutrons) was 1.4×10^{10} n/cm^2, and the Pu flux (from 200 ev to above 3 Mev) was 1.2×10^{11} n/cm^2.

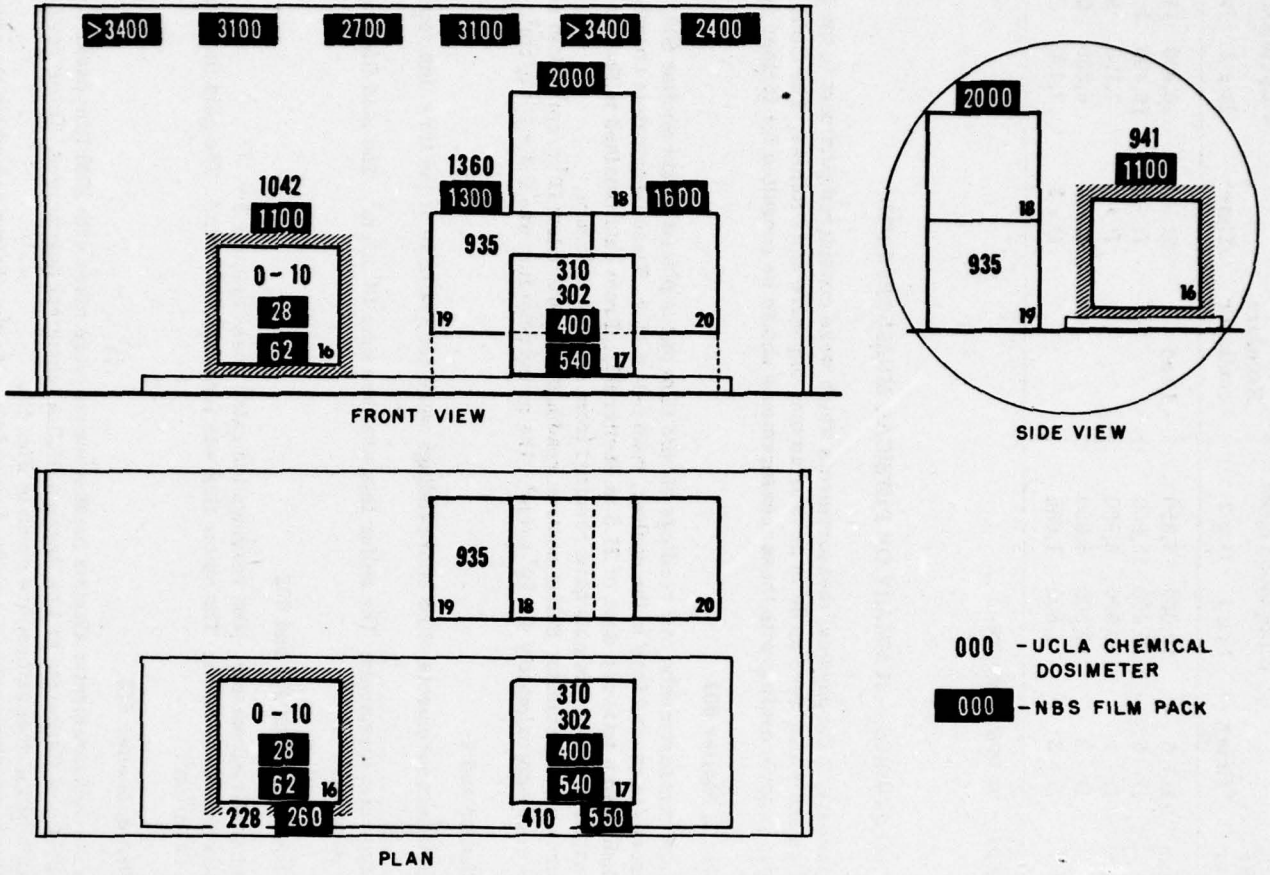

Fig. 4.9—Distribution of dosage within Shelter 613, shot 8.

4.3.5 Shot 11

Gamma measurements: Apparently, a sharp gradient of gamma dose existed within the shelter.[7] Readings of UCLA chemical dosimeters placed near the exposure cubes housing dogs and mice indicated doses between 545 and 700 r.

Neutron measurements: Within the aluminum cube, the sulfur and gold fluxes were 4.7×10^9 n/cm^2 and 2.9×10^{10} n/cm^2, respectively. Corresponding readings in the lead cube were 1.2×10^9 n/cm^2 and 1.4×10^{10} n/cm^2.

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CHAPTER 5

DISCUSSION

5.1 DATA OBTAINED WITH BIOLOGICAL INDICATORS

The equipment designed for exposure of animals in the shelters functioned satisfactorily. With the exception of a few deaths which occurred in shot 1 and were attributable to primary blast injury (see Appendix B), all other animals were recovered alive and apparently in excellent condition. The values obtained on field-stressed animals exposed under conditions as nearly identical as possible to those of the actual detonation did not differ appreciably from unirradiated X-ray control animals observed at approximately the same time; hence it may be concluded that the effect of the stress of exposure was minimal and controlled adequately for most end points employed. One exception that deserves comment is the uptake of radioactive iron in hematopoietic tissue. It was found repeatedly that stress in the field (leaving mice overnight in the exposure containers with heat and ventilation) depressed the uptake of iron by as much as 50 per cent. This depression does not occur in the laboratory with the mild stress incident to X irradiation. The reason for the depression is not clear, and further work to determine the cause is indicated.

Data obtained on mice X-irradiated at the test site showed satisfactory agreement in general among the several studies performed at different times.

5.2 DATA OBTAINED WITH PHYSICAL DETECTORS

The present biological field experiments were more thoroughly instrumented than were those of any previous similar operation. Care was taken to have detectors placed as near the animals as possible. In addition to instrumentation within the exposure cubes, detectors were frequently placed within the wire-mesh mouse cages. In all exposure situations NBS film packs, sulfur buttons, and gold foils were placed with the animals. Whenever possible, UCLA chemical dosimeters and fission detectors were added. In two shots (1 and 8) the manganese flux was determined in the shelters containing animals in an effort to measure the intermediate-energy flux for possible correlation with biological response.

Hence it is possible to estimate the physically measured dose in the immediate proximity of the animals and to attempt correlations between physical measurements and biological response.

5.3 PROBABLE BIOLOGICALLY EFFECTIVE DOSE WITHIN SHELTERS

In Shelters 601 and 602 all biological end points consistently indicated essentially zero dose (Table 4.9). These shelters were 500 yd from shot 1, and in shot 8 Shelter 601 was 776 yd

from the bomb. Shots 1 and 8 were tower shots with yields of 17.8 and 32.4 kt, respectively. The dose within these shelters, under all conditions tested, can be considered of minimal or of no significance biologically.

In Shelter 7.9.1b the total dose within the shelters in shots 3 and 4 was too low to be measured biologically. Shot 3 was a tower shot (0.18 kt) at a slant distance of 650 yd, and shot 4 was an air burst (10.8 kt at ~2007 yd). In shot 11 the total dose measured biologically within the aluminum cube was 700 rem or greater; the neutron dose as measured within the lead cube was approximately 100 rem. The dose as measured physically varied greatly with position in the shelter (see Sec. 5.4). Shot 11 was an air burst (60.0 kt) detonated at 600 yd slant range.

Shelter 613 was used on shot 8 only (tower shot, 32.4 kt), and the earth was cut away in front in an attempt to simulate an airdrop. The total dose as measured biologically ranged from approximately 400 rem to an excess of 1000 rem, depending on position within the structure (see Sec. 5.4). Within the lead-shielded cube a total dose slightly below the minimum detectable dose of about 60 rem was indicated by the spleen and thymus end points. Animals exposed in a similar position in the shelter in an aluminum cube indicated a total effective dose of approximately 400 rem. These findings indicate that the contribution of neutrons to the total biologically effective dose may have been roughly 10 per cent, a figure approximately equal to the probable neutron contribution to the total ionizing radiation dose in free air at these distances from the weapons used.

5.4 EFFECT OF SHELTER OVERLAY THICKNESS ON INTERIOR RADIATION DOSE

Since no appreciable neutron effects were detected biologically in Shelters 601 and 602 (shots 1 and 8), nor in Shelter 613 (shot 8, simulated air burst), the conclusion is warranted that with the large-diameter implosion weapon, and with an outside neutron flux of 2.4×10^{11} or below, an earth covering of 3 ft 8 in. on all sides of the shelter is adequate to reduce neutron dosage to acceptable levels biologically. The data, however, do not allow predictions for less than 3 ft 8 in. of earth covering or for higher incident neutron fluxes.

Although gamma radiation constituted no hazard in Shelters 601 and 602 (tower shots), the doses obtained of greater than 600 rem in Shelter 7.9.1b (shot 11, air burst) and in Shelter 613 (shot 8, simulated air burst) indicate that gamma radiation may be a possible hazard with a large kt overhead burst at close range. The gamma levels obtained should be regarded as maximal, however, since the structures employed were rough prototype shelters and radiation leaks very likely occurred in both instances (see Sec. 5.5).[1]

The biologically effective neutron dose relative to the accompanying gamma-ray dosage does not appear to increase over the free-air situation following transmission of the immediate bomb radiation through an earth shield. Hence the maximum neutron dosage contribution and the total radiation hazard within the shelter can be estimated accurately from gamma dosage measurements. It is clear from the data that gamma was the chief or "controlling" radiation hazard within the shelters as studied. This fact was evident in Shelter 613, shot 8, and was confirmed in the data obtained on shot 11. The dosage in the region of the exposure cubes in shot 11 was in excess of 600 rem, whereas the neutron contribution as measured biologically within the lead cube was approximately 100 rem. This is the contribution of neutron dosage to the total effect seen that would be expected in the free-air situation.

An estimate of the effectiveness of earth as an attenuating medium under the condition employed can be obtained from the summary of physical data (obtained from Ref. 2) in Table 5.1.

The LD_{50} for mice exposed to bomb neutron radiation is approximately 2×10^{10} sulfur n/cm^2 as measured free in air.[3] This figure is for mice exposed in 7-in.-thick lead hemispheres, which are presumably essentially transparent to neutrons; hence the mice reflect the free-air situation. It is seen, therefore, that the neutron dose outside the shelters would have been lethal in most instances. An appreciable neutron dose within the shelters was obtained only with a large weapon (shot 11, 60.0 kt) at close range, and the neutron flux was accompanied by an excessive dose of gamma radiation.

Table 5.1 — DATA FROM UPSHOT-KNOTHOLE PROJECT 23.17

Shot No.	Shelter No.	Sulfur flux, n/cm^2		Gamma dose, r	
		Outside	Inside	Outside	Inside
1	602	2.4×10^{11}	$<10^7$	27,000	<25
8	601	1.7×10^{10}	$<10^7$		<25
	602	9.7×10^9	$<10^7$		<25
	613	1.9×10^{10}	$\simeq 10^7$		300–3000
11	7.9.1b	5.5×10^{11}	3×10^9	150,000	250–3000

5.5 RELATION BETWEEN BIOLOGICAL AND PHYSICAL MEASUREMENTS

In general, the doses indicated by the biological dosimeters employed agreed remarkably well with the physical measurements of dose. In Shelters 601 and 602, both in shots 1 and 8, all indicators agreed in that the dose in the shelters was negligible. Similarly in shots 3 and 4, Shelter 7.9.1b, all dosimeters indicated essentially zero dose. In Shelter 613, shot 8, and in Shelter 7.9.1b, shot 11, a different situation existed.

In Shelter 613, shot 8, mice in different positions within the aluminum cube indicated different doses. Mice placed in the first or highest of five shelves in the cube indicated approximately 875 rem (gut weight), whereas mice on the third and fourth shelves down indicated doses of approximately 400 rem (spleen-thymus and mortality, respectively). The mice for gut weight determinations and those for spleen-thymus or mortality observations were separated by at least 10 in. Physical dosimeters placed on the second shelf from the top indicated 302 and 310 r (UCLA chemical dosimeters) and 400 and 540 r (NBS films). The discrepancy between readings from gut weights and the spleen-thymus end point may be due in part to the relatively greater rem dose indicated by the gut weight following fast-neutron exposure (see Appendix A). It would appear more likely, however, that the marked gradients in dose within the shelter might have been chiefly responsible.

Gamma measurements indicated that the dose within Shelter 613 varied from 3000 r approximately 2 ft from the top to approximately 250 r in front of the cubes near the floor. This gradient could account easily for the marked difference in dose received by objects separated only by several inches. Dosimeters placed on top of the aluminum mouse cube and within the cube (approximately 10 to 15 in. apart, separated by $\frac{1}{4}$ in. of aluminum) gave results differing by a factor of 3 (see Fig. 4.9). Similar results were obtained with dosimeters placed inside and outside the aluminum dog cubes.

The dose gradient was indicated also by the dogs exposed in the aluminum cubes. The two dogs in the upper cube vomited before recovery and gave indications of having received well in excess of 1000 rem. Dogs exposed in the lower cubes indicated exposure of between 600 and 1000 rem.

Gamma measurements within the aluminum mouse cube gave readings of from 302 to 540 r. The response of the mice (about 400 rem) was consistent with these findings. Gamma measurements within the lower aluminum dog cubes were approximately 950 r. The response of the dogs in these cubes was consistent with this reading. Readings of NBS film packs placed on top of the upper aluminum dog unit were approximately 2000 r, and the dogs in this unit reflected a dose of this magnitude.

Mice placed within the cube shielded with 3 in. of lead indicated a dose just below the minimal detectable dose of approximately 60 rem using the spleen-thymus end point and approximately 130 rem using the white blood count end point. These results are consistent with neutron exposure of approximately 60 "thymus rem," since data from Tumbler-Snapper and the present series on mice exposed in lead hemispheres indicate that, at doses below approximately 200 thymus rem, the white blood count may indicate a greater exposure than does the thymus (above 200 rem the white count indicates a lower exposure than does the thymus). The gamma readings within the lead cube were less than 10 r according to the UCLA chemical dosimeter and 28 and 62 r according to the NBS film packs. The sulfur neutron measurement within the cube was less than 10^7 n/cm^2, and the gold flux was 3×10^{10}, both of which are insignificant biologically. The fission detector and manganese fluxes (1.3×10^{11} and 1.4×10^{10} n/cm^2, respectively), indicated only moderate intermediate-energy neutron fluxes within the structure. It is not impossible, therefore, that the biological response seen within the lead cube, consistent with neutron exposure, may have resulted from exposure to a disproportionately high intermediate-energy neutron flux compared with either the gold or sulfur flux measured. It is emphasized, however, that the biological response seen was small and probably of little significance.

On shot 11 the response seen in both mice and dogs exposed in the aluminum containers was consistent with the readings of approximately 1000 r obtained with UCLA chemical dosimeters placed near the cubes. The dose within the lead cube was approximately 100 rem measured biologically. The sulfur neutron dose measured in the vicinity of the lead cube varied from approximately 1×10^8 to 1×10^9. These values are not in marked disagreement with the biologically measured dose. The variation in dosage with position within the shelter and the single biological end point obtained on the relatively small number of mice exposed do not warrant attempts to accurately compare biologically and physically measured dose.

5.6 RELATION BETWEEN BIOLOGICAL OBSERVATIONS ON SMALL AND LARGE ANIMALS

In all instances the response seen in dogs was consistent with that expected from effects seen in mice. No detailed comparisons can be made, however, since the accurate quantification obtained with large, uniform samples of mice cannot be approached with the small numbers of mongrel dogs employed.

REFERENCES

1. Ellery Storm, Gamma Radiation Exposure as a Function of Distance, Tumbler-Snapper Project 15.2 Report, WT-549, 1952.
2. E. Tochilin et al., Neutron Flux Measurements Within Communal Shelters and Lead Hemispheres, Upshot-Knothole Project 23.17 Report, WT-795, September 1953.
3. J. T. Brennan et al., The Biological Effectiveness of Neutron Radiation from an Atomic Bomb, Greenhouse Report, Annex 2.4, Part I, Sec. 2, WT-43, 1951.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Measurement of the total radiation hazard within earth-protected AEC communal shelters by exposure of biological material was carried out in five shots of the Upshot-Knothole series. Animals were exposed in $\frac{1}{4}$-in. aluminum and in lead-protected containers in order to estimate the neutron contribution to the total biologically effective dose. Mice and dogs were used, and biological end points employed included mortality, hematology, spleen-thymus weights, gut weights, and uptake of radioactive iron in hematopoietic tissue.

Results and conclusions of the studies are summarized as follows:

1. Satisfactory correlations between physical measurements of dose and biological effects were obtained.

2. For shelters with minimum earth overlay thickness of approximately 3 ft 8 in., the neutron flux within the shelters did not constitute an appreciable hazard when the outside sulfur flux was 2.4×10^{11} n/cm^2 or less. Sulfur fluxes of this order of magnitude are encountered at distances of approximately 700 yd from a 20-kt weapon.

3. The data do not permit predictions for fluxes of greater than 2.4×10^{11} n/cm^2 with 3 ft 8 in. of earth shielding or for less shielding with the same flux, but they indicate that fast neutrons may constitute a hazard under either extreme situation.

4. Under the conditions employed it appeared that the attenuation of neutrons observed was less dependent on the slant range of earth through which the neutrons passed, since it was on the minimum thickness of earth over the shelter.

5. The contribution of neutrons to the total biologically effective dose does not increase over the free-air situation following transmission of the bomb radiation through the protective earth covering. Therefore gamma rays constitute the chief or controlling radiation hazard within the shelters exposed to large-diameter implosion weapons.

6. With tower shots the dose of gamma radiation within the shelters was negligible. With conditions approaching those of a direct overhead shot, using comparatively crude prototype structures, significant levels of gamma radiation were observed. No statement of absolute levels of dosage to be expected in the shelters are warranted from the data, however, because of the high probability of gamma leaks in the structures studied.

CHAPTER 7

RECOMMENDATIONS

1. Since the contribution of neutrons to the total radiation hazard is not increased in the shelters over the free-air situation, it would appear that further assay of the neutron hazard within the shelters by exposure of animals is not indicated. The earth-shielded shelters offer no advantage over the free-air situation in the study of neutron effects on animals.

2. The gamma-ray hazard within the shelters can be evaluated adequately with readings of physical dosimeters; therefore further exposure of animals within the shelters to assess the gamma-ray hazard is not warranted.

3. The complete shelters should be tested with airdrop, in addition to tower shots, in order to evaluate more adequately the relative importance of slant thickness vs minimal earth overlay in determining the degree of transmission of both neutrons and gamma rays.

4. Since neutrons may, in free air and in certain shielded conditions,[1] be responsible for a large percentage of the total hazard from ionizing radiation, it is recommended that further studies of the effects of total-body neutron irradiation, particularly on large animals, be conducted. It is recommended that all possibilities of conducting such studies in the laboratory be exhausted before field testing is resorted to, because of the inherent difficulties in, and the large cost of, such field operations.

REFERENCE

1. R. E. Carter et al., The Biological Effectiveness of Neutron Radiation from the Artillery-Shell Weapon on the Ground Surface and in Foxholes, Upshot-Knothole Project 4.8 Report, WT-747 (in preparation).

APPENDIX A

DATA OBTAINED ON MICE EXPOSED IN LEAD HEMISPHERES ON SHOT 9

CF_1 mice were exposed in 7-in.-thick lead hemispheres placed at varying distances from shot 9 (Encore). The distance between predicted and actual Ground Zero was considerable, and as a result the dosage received in all but the three stations farthest from the weapon exceeded the range of interest for the experiment. The minimal amount of data obtained is presented in this appendix.

The exposure apparatus, technique of exposure, etc., are described fully in other reports.[1-3] A total of 53 mice were placed in each of 11 hemispheres; 18 mice for spleen, thymus, and blood count studies; 18 for mortality rate observation; and 17 for gut weight determinations (no mice for gut weight or for mortality rate determinations were placed in Station S). The results obtained are presented in Table A.1. The mean values for each end point are listed, and the corresponding rem dose as determined from X-ray control studies (see Sec. 4.1) is given in parentheses below the mean. Pertinent physical data are presented in Table A.2.

Table A.1 — DATA OBTAINED ON MICE EXPOSED IN LEAD HEMISPHERES, SHOT 9

Station	Mean spleen weight, mg	Mean thymus weight, mg	Mean white blood count	Mean gut weight, mg	30-day mortality, %	Mean survival time, hr
A–L	*	*	*	173 (900)	100	67–72
N	*	*	*	174 (910)	100	72
O†	21.0 (575)	11.4 (590)	1010 (250)	191 (770)	94	75
S	36.6 (360)	38.3 (220)	1353 (210)			
Control	113.2	77.1	5350	290		

* All animals were dead by the fifth postirradiation day.
† Only 13 animals were alive on postirradiation day 5.

Table A.2 — PHYSICAL DATA FROM SHOT 9

Station	Slant range, yd	Sulfur flux, n/cm²		Gold flux, n/cm²		Inside gamma, r
		Inside	Outside	Inside	Outside	
N	873	3.85×10^9	2.08×10^{10}	2.60×10^{11}	2.21×10^{11}	7
O	905	3.22×10^9	1.68×10^{10}	1.80×10^{11}	2.01×10^{11}	6
S	1023	1.81×10^9	8.58×10^9	9.10×10^{10}	8.94×10^{10}	4

The quantity of data obtained obviously is insufficient to warrant extensive conclusions. In general, the data agree with previous findings on mice exposed in the lead hemispheres. The white blood count again indicated a lower rem dose than did the spleen-thymus in the dose range encountered. The gut weight indicated a rem dose considerably larger than did the other end points. This may reflect the presumably greater relative sensitivity of the gut to neutrons.[2] The dose received at Station S was just sufficient to reduce the mean thymus weight by a factor of 50 per cent over that of the controls. The sulfur neutron dose (outside) at this station was 8.58×10^9. This value is considerably larger than the corresponding figure obtained in previous operations (approximately 1 to 3×10^9 in Operations Greenhouse and Tumbler-Snapper).

The short survival time previously reported[2] in neutron-exposed mice was again a striking observation. Hourly checks on mortality were made at the peak time of death, and accurate mean survival times were obtained. Mean survival times in the nine stations where 30-day mortality was 100 per cent (18 mice per station) ranged from 67 to 72 hr, and the average was 71.2 hr.

REFERENCES

1. R. E. Carter et al., The Biological Effectiveness of Initial Gamma Radiation from an Atomic Weapon, Greenhouse Report, Annex 2.4, Part I, Sec. 1, WT-43, 1951.
2. J. T. Brennan et al., The Biological Effectiveness of Neutron Radiation from an Atomic Bomb, Greenhouse Report, Annex 2.4, Part I, Sec. 2, WT-43, 1951.
3. R. E. Carter et al., The Biological Effectiveness of Neutron Radiation from Nuclear Weapons, Tumbler-Snapper Project 4.3 Report, WT-528, 1952.

APPENDIX B

BLAST DAMAGE IN MICE WITHIN THE EXPOSURE CUBES

A total of 33 mice out of approximately 800 exposed were found dead on recovery from shot 1. Autopsy revealed petechial and gross hemorrhages in the lungs and, frequently, blood in the pleural cavity. The surviving animals were active and appeared normal. There was no evidence of blast damage to the exposure apparatus, and the animals were considered to have died from the effects of primary blast. There was no further mortality among exposed mice observed over a 30-day period.

Essentially all deaths occurred in units 5 and 6 (see Fig. 3.2), placed close to the junction of the concrete and metal culvert sections. One death occurred in unit 1, placed near the shelter door. Essentially all deaths occurred in the left half of the units and in the top two rows of wire-mesh cages. The numbers dying in each specific location are indicated in Table B.1. (The wire-mesh cages in the quadrant on the left nearest the door are numbered 1 to 5 from top to bottom; the five in the left rear quadrant are numbered 6 to 10; the five in the right front quadrant are numbered 11 to 15, etc.).

Table B.1 — MICE DYING IN DIFFERENT LOCATIONS

Unit No.	Wire-mesh cage No.	No. of mice dying
1	16	1
5	2	2
	3	2
	6	3
	7	2
7	2	9
	6	2
	7	12

All cubes were closed during the detonation. Ventilation holes in the cubes (about $1\frac{1}{2}$ in. in diameter) were placed as follows: right side (facing the cube), 2 holes at the level of the top row of wire-mesh cages (see Fig. 3.6); left side, a single hole, forward, at the level of the top row; front, same as left side. No other openings were present with the exception of a 3-in.-diameter hole on top of the unit over cage number 16, closed for the most part by the blade and supports of a ventilating fan in operation at the time of the detonation.

The explanation for the peculiar distribution of blast deaths within the cubes is not apparent.

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